PB-249 361

EVALUATION OF A PNEUMATIC BARRIER FOR OIL CONTAINMENT

John M. Grace

Calspan Corporation

Prepared for:

Industrial Environmental Research Laboratory

February 1976

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-76-030		

4. TITLE AND SUBTITLE	5. REPORT DATE
EVALUATION OF A PNEUMATIC BARRIER FOR OIL CONTAINMENT	February 1976
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Grace, John M.	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Calspan Corporation (Cornell Aeronautical Laboratory, Inc.) P. O. Box 235 Buffalo, New York 14221	1BB610
	11. CONTRACT/GRANT NO. Grant WPRD 263-01-68 Project 11020 DJG

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Industrial Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	Final 7/68 - 2/71
	14. SPONSORING AGENCY CODE EPA-ORD

15. SUPPLEMENTARY NOTES
One of five portions of the final report under this Grant. See also EPA-600/2-76-027, 028, 029, and 031

16. ABSTRACT

The investigation reported herein concerns the development and evaluation of a pneumatic barrier for restraining the natural flow of surface oils in the Buffalo River. The initial phase of this study involved laboratory experiments to evaluate the surface currents produced by bouyant air-water plumes which were formed by the injection of air through single and multiple orifices submerged below the water surface. Based upon the data obtained in the laboratory experiments, a full scale, prototype air barrier system was designed. This barrier system was built and installed in the river. A full scale test program was initiated in order to evaluate the performance of the barrier. Following the river test phase of the program, additional laboratory tests were conducted in a water channel facility to investigate the performance of a barrier system at higher currents and for different oil types than were available in the Buffalo River.

It was determined that a pneumatic barrier could be an effective device for stopping the flow of surface oils for currents less than one foot per second. The actual limiting speed for a particular oil was a function of its viscosity and specific gravity. In no instance was any oil that was tested restrained in a current of more than 1.5 fps.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Barriers Oils Stream pollution	Buffalo River Pneumatic barrier Air curtain Surface oil interception Pollution abatement	13B

PRICES SUBJECT TO CHANGE

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	77
	20. SECURITY CLASS (This page)	22. PRICE
	UNCLASSIFIED	5.00-2.25

EPA Form 2220-1 (9-73)

049120

PB 249 361

EPA-600/2-76-030
February 1976

EVALUATION OF A PNEUMATIC BARRIER FOR OIL CONTAINMENT

by

John M. Grace
Cornell Aeronautical Laboratory, Inc.
Calspan Corporation
Buffalo, New York 14221

Project No. 11020 DJG

Project Officer

Richard R. Keppler
Region I
U.S. Environmental Protection Agency
Boston, Mass. 02203

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
CINCINNATI, OHIO 45268

REVIEW NOTICE

This report has been reviewed by the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The investigation reported herein concerns the development and evaluation of a pneumatic barrier for restraining the natural flow of surface oils in the Buffalo River. The initial phase of this study involved laboratory experiments to evaluate the surface currents produced by bouyant air-water plumes which were formed by the injection of air through single and multiple orifices submerged below the water surface. Based upon the data obtained in the laboratory experiments, a full scale, prototype air barrier system was designed. This barrier system was built and installed in the River. A full scale test program was initiated in order to evaluate the performance of the barrier. Following the River test phase of the program, additional laboratory tests were conducted in a water channel facility to investigate the performance of a barrier system at higher currents and for different oil types than were available in the Buffalo River.

It was determined that a pneumatic barrier could be an effective device for stopping the flow of surface oils for currents less than one foot per second. The actual limiting speed for a particular oil was a function of its viscosity and specific gravity. In no instance was any oil that was tested restrained in a current of more than 1.5 fps.

This report was submitted in fulfillment of Program Number 11020 DJG, Grant Number WPRD 263-01-68 by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.) under the partial sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

Section	Page
CONCLUSIONS	1
RECOMMENDATIONS	3
INTRODUCTION	5
INITIAL LABORATORY TESTS	7
Test Program	7
Laboratory Facility and Instrumentation	7
Test Results	10
Single-Nozzle Tests	10
Multiple-Nozzle Tests	14
DESIGN OF THE PNEUMATIC BARRIER	19
Selection of the Pneumatic Barrier Site	19
Components of the Pneumatic Barrier System	23
Air Manifold	23
Anchorage of the Air Manifold	23
Nozzle Construction and Configuration	23
Air Supply	27
RIVER TEST PROGRAM	29
Test Measurements	29
Test Data Analysis	30
Limitations of the Installed Pneumatic Barrier System	35
Wind Effect on Barrier Performance	35
ADDITIONAL LABORATORY EXPERIMENTS	39
Introduction	39
Modeling	39
Test Program	41
Velocity Profiles	41
Formation of Stagnation Zone	47
Testing of Oils in a Channel	47
Results of Tests on Surface Oils	51
PNEUMATIC BARRIER FAILURE MECHANISMS	55
POWER REQUIREMENTS	65
ACKNOWLEDGMENTS	69
REFERENCES	71

FIGURES

No.		Page
1	Water Tank Test Facility	8
2	Test Configuration of Buffalo River Pneumatic-Barrier Prototype Installed in CAL Water-Tank Test Facility	9
3	The Effect of Supply Pressure on Surface Velocity (Test of 1-1 mm Orifice)	11
4	The Effect of Supply Pressure on Surface Velocity (Test of 1-2 mm Orifice)	11
5	The Effect of Supply Pressure on Surface Velocity (Test of 1-3 mm Orifice)	12
6	The Effect of Supply Pressure on Surface Velocity (Test of 1-3 mm Orifice in Two Configurations)	13
7	The Effect of Orifice Spacing on Surface Velocity As a Function of Nozzle Depth	15
8	Distribution of Surface Velocities Normal to Manifold (Test of a Series of 1 mm Orifices at 1 Foot Spacing - Supply Pressure 50 psig)	17
9	Distribution of Surface Velocities Normal to Manifold (Test of a Series of 2 mm Orifices at 1 Foot Spacing - Supply Pressure 20 psig)	17
10	Distribution of Surface Velocities Normal to Manifold (Test of a Series of 2 mm Orifices with 2 Foot Spacing)	18
11	Map of the Buffalo River	20
12	Aerial View of Buffalo River Pneumatic-Barrier Site at Michigan Avenue Lift Bridge	21
13	Buffalo River Bed Contour - South Michigan Avenue Bridge Site	22
14	Pneumatic Barrier, Tubes, Anchor Blocks and Cables	24
15	Schematic of Pneumatic Barrier in Buffalo River	25
16	Pneumatic Barrier Shore Anchor	26
17	1 mm and 2 mm Nozzles	28
18	Effect of Supply Pressure on Δ	31
19	Effect of Volumetric Flow Rate on Δ	32
20	Effect of the Volumetric Flow Rate on Δ^* for Various Supply Pressures	33
21	Effect of River Velocity on Δ^*	34

FIGURES (Cont.)

No.		Page
22	Variation of Surface Velocity on One Day	36
23	Typical River Velocity Profiles Obtained at Various Times on One Day	37
24	Water Channel Test Facility	40
25	Schematic of Air Manifold in Water Channel	40
26	Coordinates Used in Pneumatic Barrier Investigation	43
27	Water Channel Velocity Profile	44
28	Water Channel Velocity Profile	45
29	Water Channel Velocity Profile	46
30	Effect of Volumetric Flow Rate on Δ	48
31	Plexiglass Channel	49
32	Surface Photo #2 Fuel, V = 0.7 fps	52
33	Subsurface Photo #2 Oil, V = 0.7 fps, Scale $\approx$2X	53
34	Typical Surface Bubble Pattern	56
35	Approximation of the Velocity Profile Generated by Pneumatic Barrier Operating in a River Current	57
36	Vortex Effect on Oil Surface (Viewed from Just Below Surface)	58
37	Neighborhood of the Stagnation Zone	60
38	1st Stage Film Tearing	61
39	2nd Stage Film Tearing	62
40	3rd Stage Film Tearing	63
41	Horsepower vs Volumetric Flow Rate	66
42	Horsepower vs River Current	67

TABLES

No.		Page
1	Effect of Change in Air Supply with Constant Flow Rate	14
2	Effect of Constant Pressure with Varied Flow Rate	14
3	Manifold Configurations	42
4	Typical Values for Richardson Numbers	42
5	Properties of Oils Tested	50
6	Failure Velocities for Different Oil Types	51

CONCLUSIONS

1. Pneumatic barriers can be designed, built and installed in a river to restrain surface oils in low currents of less than one foot per second.

2. The stream current at which a pneumatic barrier fails to restrain surface oils is dependent on oil viscosity and specific gravity. The currents at which serious breakthrough was found to occur for different oil types tested in the program are shown below.

OIL TYPE	CURRENT AT WHICH SERIOUS BREAKTHROUGH OCCURS
#2 Fuel	0.7 fps
#6 Fuel	1.3-1.5 fps
Bachaquero Crude	0.8 fps
South Louisiana Crude	1.0 fps

3. A single pneumatic barrier can be an economical device for restraining oil for unidirectional currents less than 1 foot per second.

4. Multiple pneumatic barriers located near the source of oil are suggested for containing oil in rivers in which there are frequent changes in current direction as is the case for the Buffalo River.

5. A system of two or more pneumatic barriers could provide an effective means for containing oil spills on the Buffalo River since most of the time the flow is less than 1 foot per second.

6. The air required to form a stagnation zone (a necessary but not sufficient condition to restrain oil) increases from 4 scfm/ft for a 1 fps current to 100 scfm/ft for a 2.5 fps current.

RECOMMENDATIONS

As a result of the laboratory and field tests of pneumatic barriers performed on this program, the following recommendations are presented.

1. It is recommended that further experimental work be undertaken to investigate modifications to pneumatic barrier design and deployment that will increase their utility. Specific areas to be considered are:

   a) Placement of the pneumatic barrier at an angle to the flow to induce a cross stream current to divert oil toward the shore.

   b) Placement of a series of jets near, but beneath, the surface of a stream to insure a continual recirculation of oil droplets removed from the subsurface of the oil slick.

   c) Modification of the flow field in the neighborhood of the stagnation zone to decrease vertical accelerations and shear forces exerted on the oil slick.

2. It is recommended that a system of two or more pneumatic barriers be designed and installed in the Buffalo River to demonstrate the long-term utility as an effective containment mechanism for occasional oil spills.

Preceding page blank

INTRODUCTION

In May 1968 the City of Buffalo made application to the Federal Water Pollution Control Administration for a Research and Development Grant for preventing and eliminating oil pollution of the Buffalo River under the provisions of the "Clean Water Restoration Act of 1966." On 24 July 1968 the City of Buffalo accepted a Federal Research and Development Grant (WPRD 263-01-68) for $552,895.00, or 75 percent of eligible costs, whichever was less. Twenty-five percent of the eligible costs have been provided by the City of Buffalo, the Buffalo Sewer Authority, the County of Erie, and the New York State Health Department in the form of either direct cash contributions or in-kind services. On 18 October 1968 a contract was negotiated with Cornell Aeronautical Laboratory, Inc. (now Calspan Corporation) of Buffalo, New York to provide the research, engineering, and development support required for the program (Calspan Corporation is the new name for Cornell Aeronautical Laboratory. Because this report was completed prior to the date of our name change (November 17, 1972), Cornell Aeronautical Laboratory (CAL) nomenclature has been retained in this document.).

The overall objective of the program was to prevent oil pollution of the Buffalo River. Specific objectives of the program were:

1) To develop, utilize and evaluate equipment and techniques for containing and removing oil in the river, including floating mechanical barriers and pneumatic barriers for preventing the movement of surface oil, oil skimmers, debris booms, and a boat containing oil and debris removal equipment

2) To develop instrumentation for detecting oil in sewers

3) To evaluate means for trapping oil in sewers

4) To devise methods for sampling oil to determine its concentration in the river, and to develop methods for analyzing the collected samples to determine their sources.

Specific aspects of the program are detailed in four separate topical reports and summarized in a summary report. This topical report describes the evaluation of a pneumatic barrier for oil containment. The other three topical reports cover detection of oil in sewers, investigation of inverted siphons for trapping oil, and oil sampling and analysis for spills in watercourses.

This investigation concerned the development of a pneumatic barrier as an efficient means to stop and accumulate surface oils in the Buffalo River. Other techniques are available for this purpose; however, many of these suffer from one or more deficiencies not present in a properly designed pneumatic barrier system. For example, a mechanical boom, which consists of a series of links of floating material extending across the river, requires constant attention by operating personnel if used on a navigable water such as the Buffalo River. In

addition, when such a boom is opened for the passage of a ship, any oil which was accumulated and not removed from the surface will pass the barrier. In contrast, a pneumatic barrier would not require constant attention by operating personnel and ensures a minimum loss of accumulated oil during ship passage. A further attribute of such a system is that it is capable of all-weather operation. As a result of these possible advantages, this part of the program investigated the feasibility of a pneumatic barrier system.

In the pneumatic barrier system, a tube is placed beneath the surface of the water and air is ejected through holes in the tube. The physical flow mechanisms that give rise to the principle of operation are as follows. As the air is ejected, the air jet breaks up into bubbles, and the cloud or plume of bubbles entrained in the water causes a local region of decreased density. The positive buoyancy force generated in this region accelerates the air-water plume in an upward direction. As this mixture rises, it entrains additional water into the rising plume, thereby causing the water near the plume to rise. At the water surface the rising column of water divides and creates a flow of water along the surface away from the axis of the plume. This surface current produced by the rising air-water plume is used to stop the flow of surface oils.

Although some work has been done theoretically and experimentally on the rise of air-water plumes in water, it has been confined to the case of rising plumes in nonflowing water. The behavior of a rising plume in a current or shear flow is still open to question and will not be answered directly in this report. The limitations of water current on the effectiveness of a pneumatic barrier in stopping oil surface films was determined.

In the past, pneumatic barriers (especially portable ones) have been used to contain oil spills. However, very little quantitative data on the operation of these devices were available at the time this study was conducted and most of the available data were derived from tests of this device as a breakwater (e.g., References 1 through 11). Although this information was useful as a guide in the present study, there remained a lack of data for the operation of a pneumatic barrier in deep water and in flowing current conditions.

The development of the present program of pneumatic barrier studies proceeded in a series of phases, each of which is discussed in this report. In the first phase, tests were conducted in Cornell Aeronautical Laboratory's (CAL) water tank to acquire an understanding of the surface current generated from single as well as multiple interacting buoyant air-water plumes. Using data from these tests, a pneumatic barrier was then designed, built, and installed in the Buffalo River. The barrier was tested full scale in the river for a variety of nozzle arrangements and environmental conditions. In the third phase, a series of tests were run in a dynamic water channel facility with current capabilities up to 4.5 feet per second. The results of these tests are presented and analyzed and conclusions drawn on the conditions under which air barriers are effective.

INITIAL LABORATORY TESTS

TEST PROGRAM

To compensate for the lack of data on the operation of a pneumatic barrier, a small experimental program was begun in the CAL water tank. The purpose of this program was to study the surface currents produced by buoyant plumes formed by the injection of air through single and multiple orifices beneath the water surface. During this program, various effects were noted:

1) The effects of variations in the geometric properties in the system (orifice diameter, spacing, depth, and direction)

2) The effect of a physical parameter (air supply pressure on surface heave, plume form, and surface velocities).

For the initial series of tests in the water tank, 1-mm-, 2-mm- and 3-mm-diameter nozzles were attached to a four-foot length of three-inch steel pipe which served as an air supply manifold. Air jets formed from the nozzles generated the buoyant plumes in this facility. Compressed air was carried via a rubber tube to the manifold from a 27.5 cfm compressor capable of delivering air at 100 psig. During this portion of the experimental program, tests of single 1-mm-, 2-mm- and 3-mm-diameter nozzles, as well as multiple arrangements of 1-mm- and 2-mm-diameter nozzles, were all carried out for manifold depths of 5, 10 and 14 feet. Later in the experimental program, tests of 1-mm and 2-mm nozzles in an 11-foot air manifold were conducted for one- and two-foot spacing and ten- and fourteen-foot submergence depths.

LABORATORY FACILITY AND INSTRUMENTATION

The Laboratory water tank used during the course of these experiments has a length of sixty feet, a width of fifteen feet and a depth of fifteen feet. A picture of this facility is shown in Figure 1. A photograph of the prototype air manifold used during the test program is shown in Figure 2. The air manifolds were placed in a vertical plane perpendicular to the side walls of the tank and located midway along the length of the tank. The vertical position of the air manifold was varied by raising or lowering a movable calibrated vertical rod which was attached to the manifold. Once the manifold was at the proper depth, the vertical rod was clamped to a horizontal supporting truss.

The surface velocities were measured with the aid of an OTT (C-1) propeller-type current meter. The output from the meter was fed to an electronic counter from which an average number of propeller revolutions could be calculated for a given time. From this average value of the revolutions per minute and the calibration chart for the

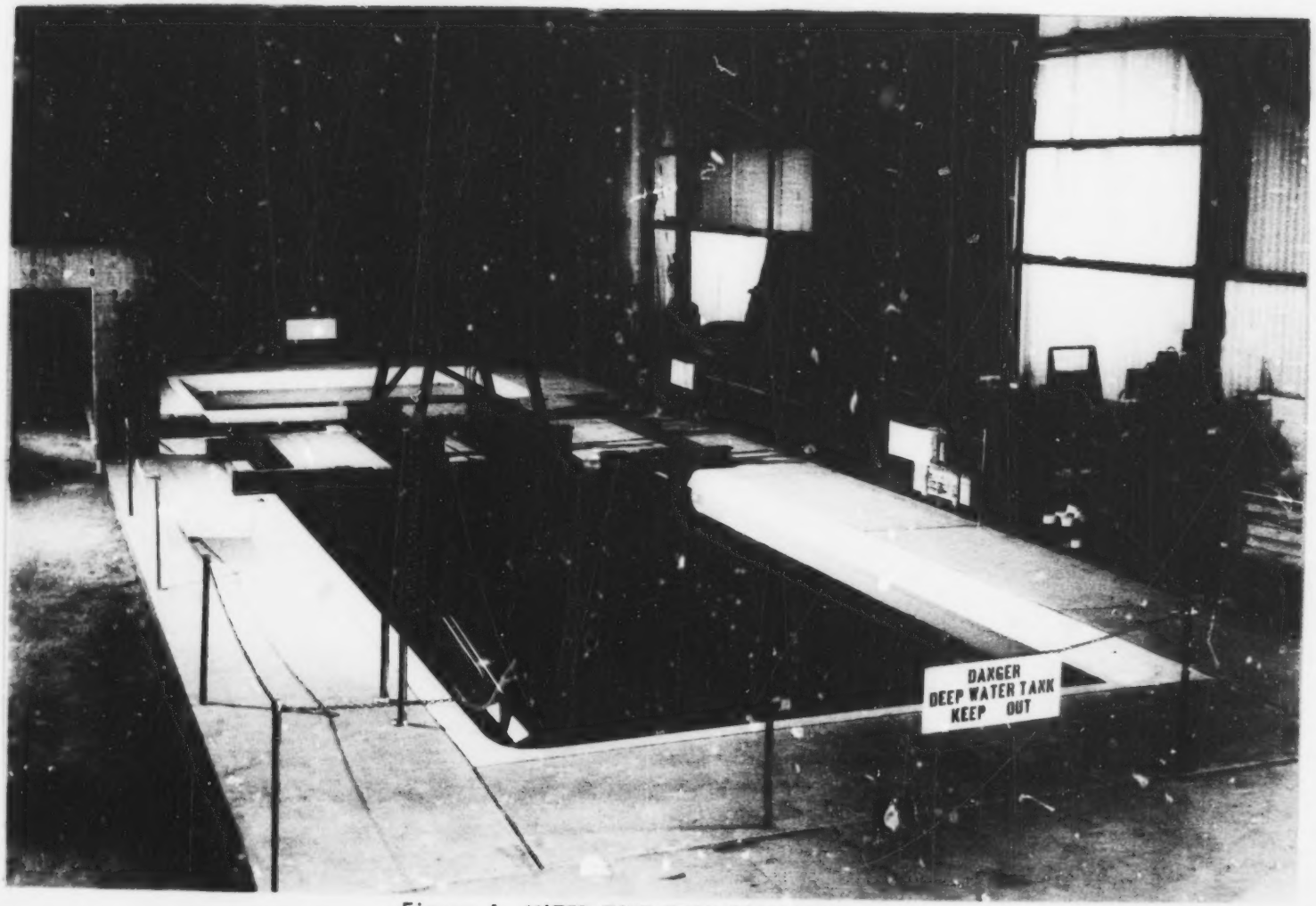


Figure 1 WATER TANK TEST FACILITY

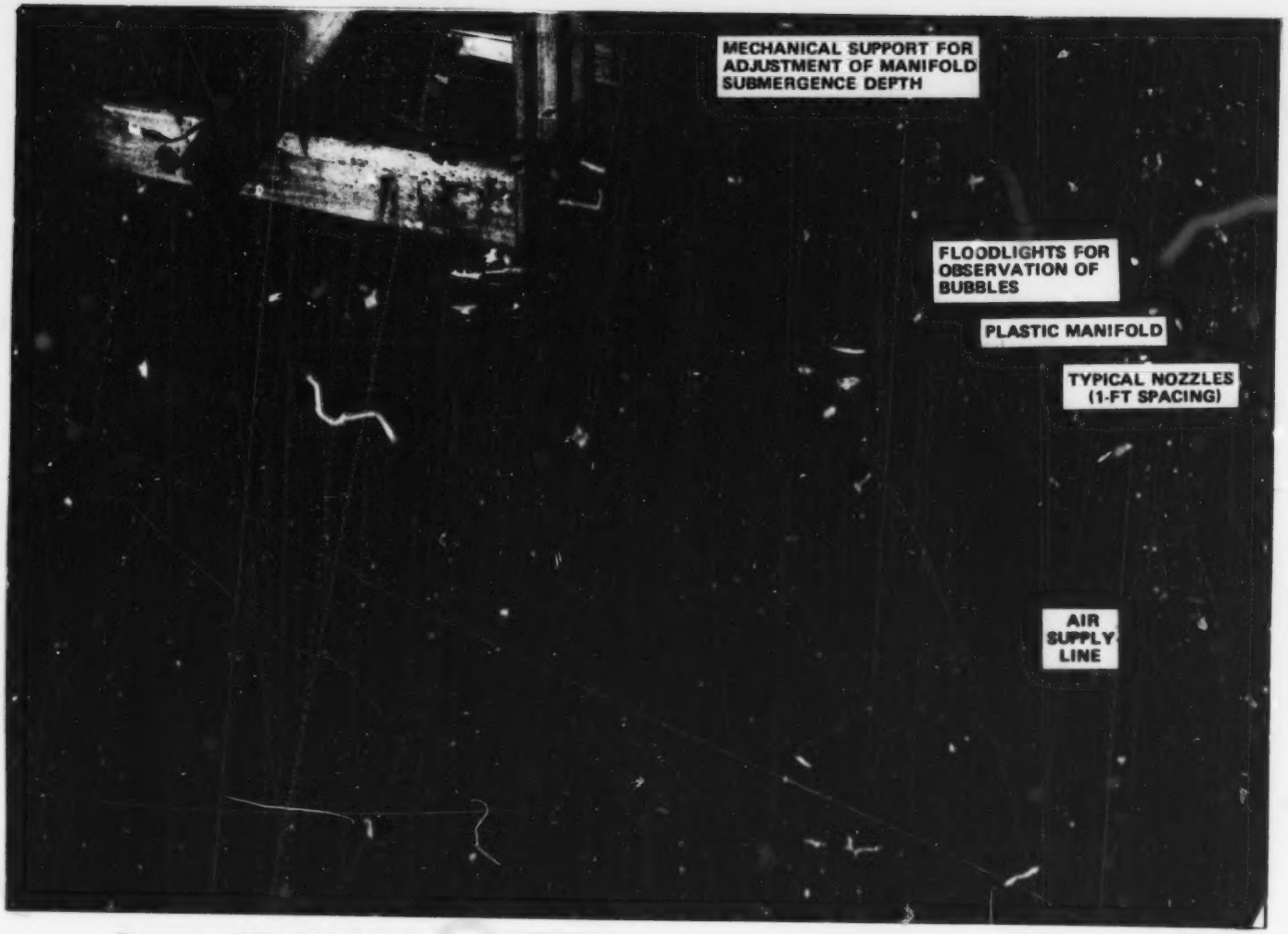

MECHANICAL SUPPORT FOR ADJUSTMENT OF MANIFOLD SUBMERGENCE DEPTH
FLOODLIGHTS FOR OBSERVATION OF BUBBLES
PLASTIC MANIFOLD
TYPICAL NOZZLES (1-FT SPACING)
AIR SUPPLY LINE

Figure 2 TEST CONFIGURATION OF PNEUMATIC-BARRIER PROTOTYPE IN WATER TANK

propeller, a value of surface velocity could be determined. The values of current noted as surface currents in the data were actually obtained at points two inches below the water surface at various positions relative to a vertical plane formed by the axis of the air manifold and a vertical line through the manifold. Surface heave measurements were made by means of a calibrated capacitance height gage. The position of this gage, which consisted of a teflon-coated stainless steel wire, was directly over the orifice or series of orifices in question during a given test.

TEST RESULTS

Single-Nozzle Tests

The surface velocities generated during the tests of the single orifice configurations are shown as a function of supply pressure in Figures 3 through 6. From these figures it is evident that there is a definite effect of submergence depth. This behavior can be related to the fact that for small submergence depths of approximately five feet the flow in the air-water mixture is confined to a small zone of high velocity fluid which forms a fountain of water at the free surface. For such a configuration there is very little opportunity for an effective transfer of vertical momentum to the water surrounding the air-water column. For larger submergence depths the initial jet region disperses and forms a rising buoyant plume which permits a longer time for transfer of vertical momentum to the surrounding water. Since surface currents produced are directly related to the vertical momentum imparted to the water by the jet and plume, one would expect to observe larger surface currents as the orifice submergence depth increases. No limitation of the depth effect can be observed from the data in Figures 3 through 6.

To determine the effect of directionality of the jet on resultant surface velocity, an experiment was conducted with a deflected and undeflected 3 millimeter-diameter nozzle. The deflection cap was placed near the jet outlet and this produced a radial outflow of air from the jet. The results of this test are shown in Figure 6 from which it is clear that there is no effect of nozzle orientation on surface currents produced for depths of ten feet or greater.

Since the surface outflow is directly related to the buoyancy force exerted on the air-water mixture, it should be expected that the more air placed in a given volume of water the greater the buoyancy force and, therefore, the greater would be the resultant surface outflow. A check of this hypothesis as well as a demonstration that the supply pressure does not have a direct effect on surface current can be derived from a further examination of the results of representative tests of single nozzles at 14-foot depths. A change in air supply pressure for constant volumetric rates effects a change in the magnitude of the surface velocity, as shown in Table 1.

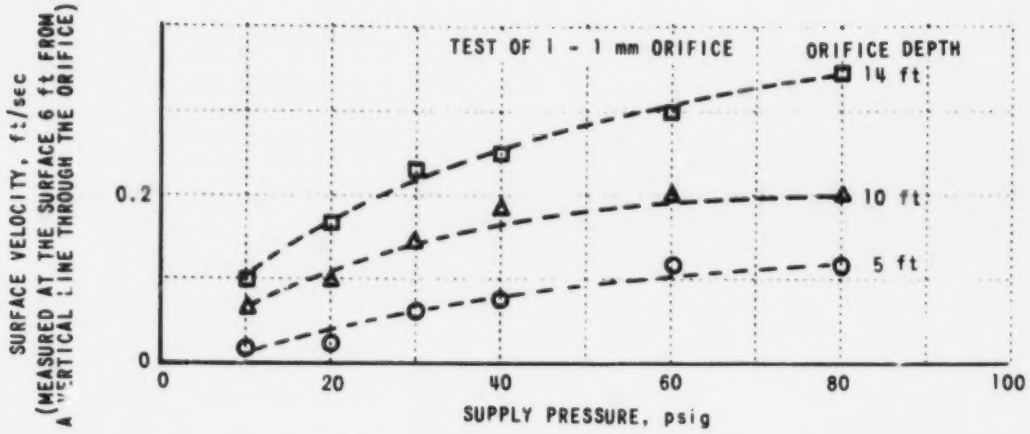


Figure 3 THE EFFECT OF SUPPLY PRESSURE ON SURFACE VELOCITY

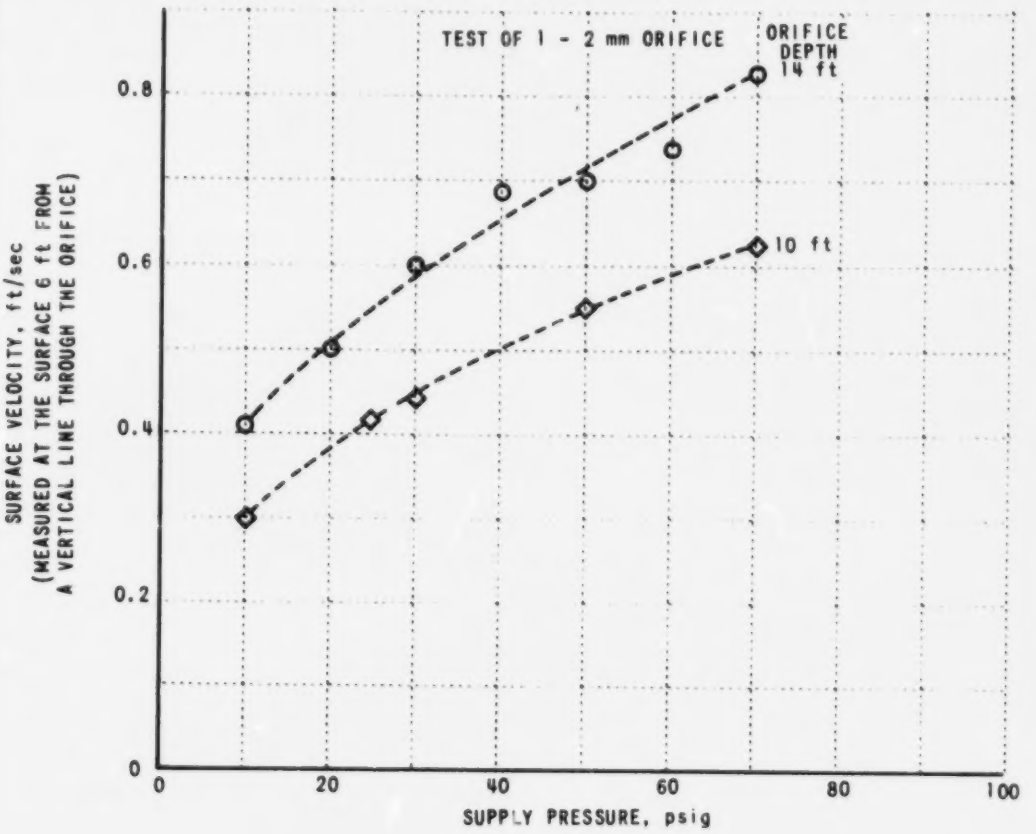


Figure 4 THE EFFECT OF SUPPLY PRESSURE ON SURFACE VELOCITY

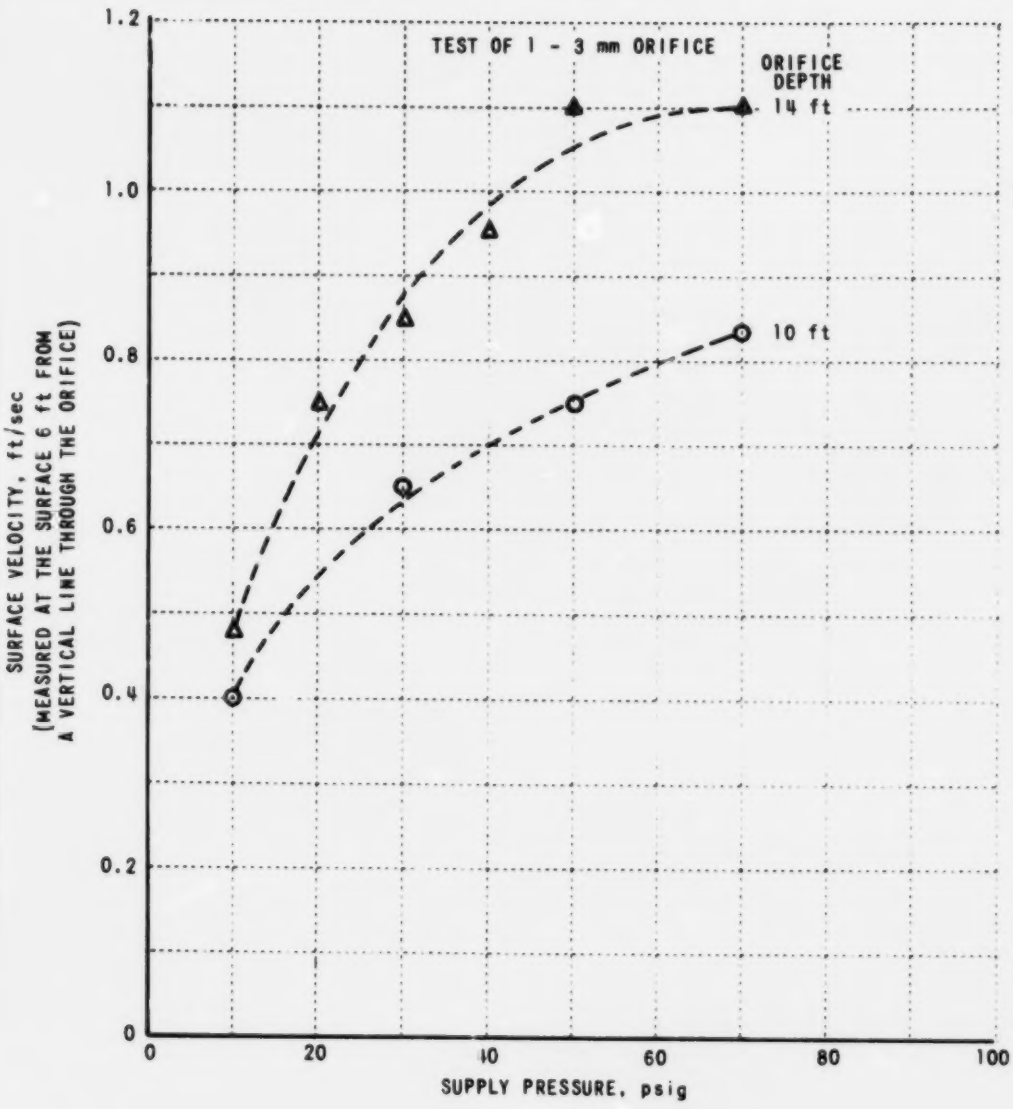


Figure 5 THE EFFECT OF SUPPLY PRESSURE ON SURFACE VELOCITY

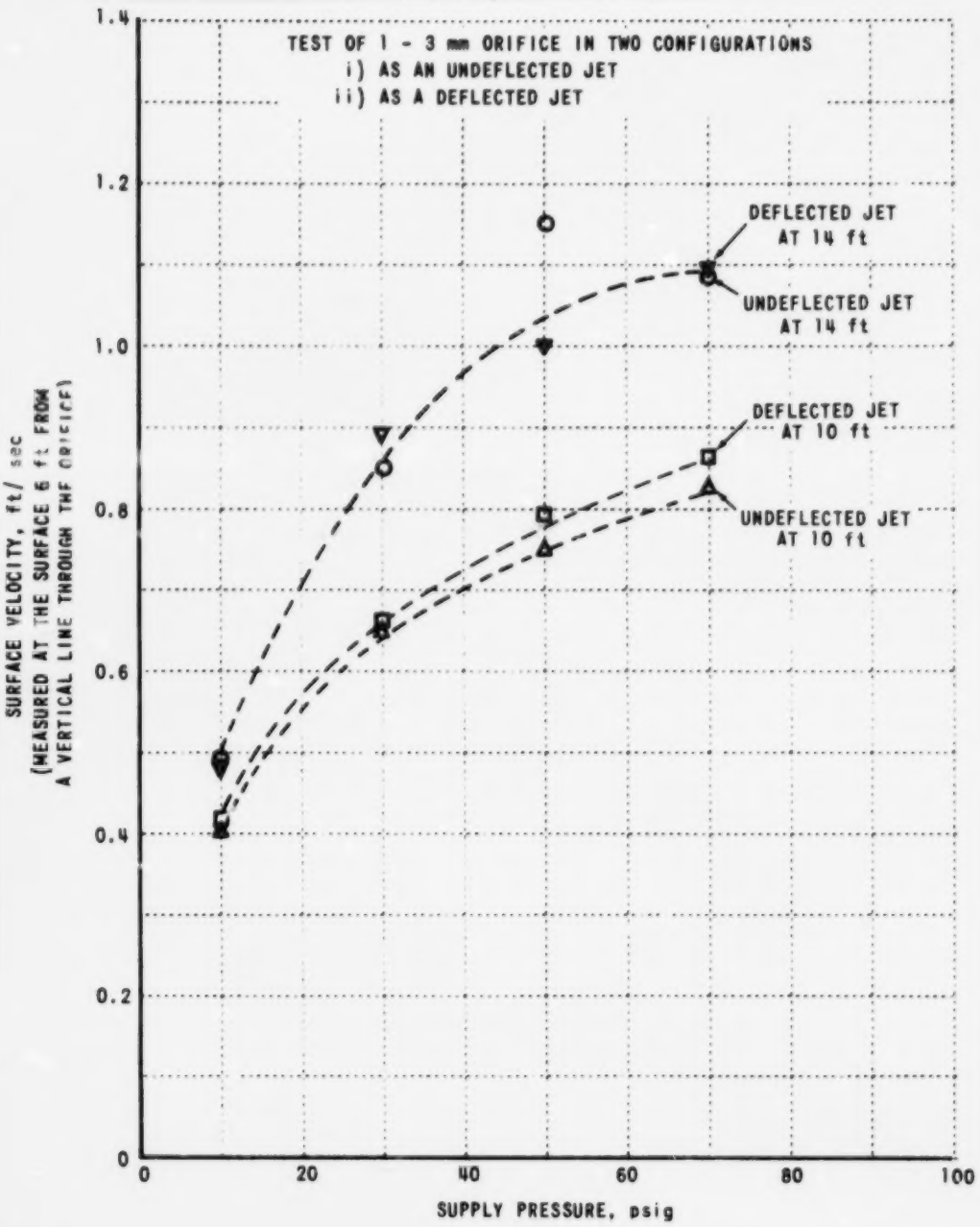


Figure 6 THE EFFECT OF SUPPLY PRESSURE ON SURFACE VELOCITY

Table 1

EFFECT OF CHANGE IN AIR SUPPLY WITH CONSTANT FLOW RATE

NOZZLE SIZE (mm)	SUPPLY PRESSURE (psig)	VOLUME RATE (scfm)	SURFACE VELOCITY (ft/sec)
3	20	8	0.75
2	70	8	0.80

In contrast to this, consider next the effect of maintaining the pressure constant but varying the volumetric flow rate. The results of these tests are shown in Table 2 below.

Table 2

EFFECT OF CONSTANT PRESSURE WITH VARIED FLOW RATE

NOZZLE SIZE (mm)	SUPPLY PRESSURE (psig)	VOLUME RATE (scfm)	SURFACE VELOCITY (ft/sec)
1	40	1.4	0.25
2	40	5.6	0.70
3	40	12.6	0.92

From the data in Tables 1 and 2 it can be inferred that the effect of increasing the air volume flow rate has a larger effect on increasing the surface velocity than does an increase in the supply pressure.

Multiple-Nozzle Tests

In addition to the single jets, multi-jet configurations were also tested. The results of a particular set of configurations are shown in Figure 7. A significant interaction effect in a multi-jet configuration can be seen in that figure. This interaction effect may be beneficial in the sense that the magnitude of surface currents produced by a particular multi-jet configuration may be higher than those produced by a single large jet having an equivalent volumetric flow rate at the same pressure. It should be noted that for the multi-jet configuration there is an indication (see test of 2 mm at 1-foot and 14-foot depths) that the surface currents change very little when the immersion depth is increased more than ten feet. The verification of this trend is important since it implies that the results of tests in water of more than ten feet in the water tank can be extrapolated to river depths.

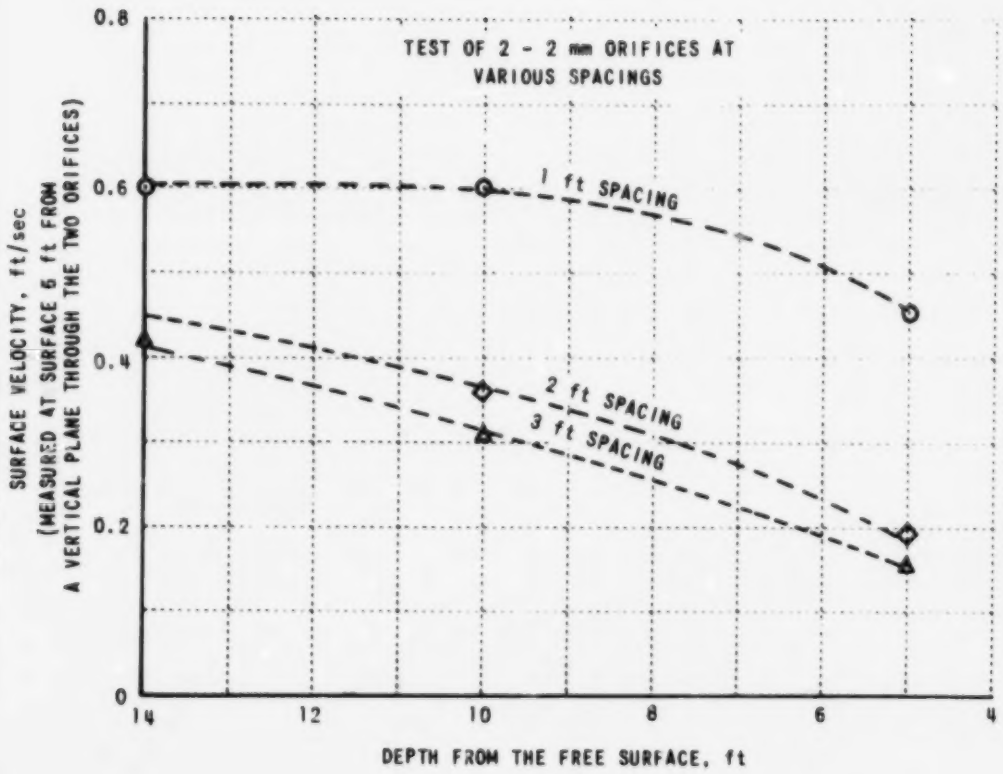


Figure 7 THE EFFECT OF ORIFICE SPACING ON SURFACE VELOCITY AS A FUNCTION OF NOZZLE DEPTH

On the basis of the previous results, further tests were suggested for a larger number of jets. Therefore, it was decided to test a multi-jet arrangement having more than two or three jets. In these tests, a further exploration of the properties of 1- and 2-mm nozzles for 1- and 2-foot spacings over the 15-foot width of the CAL tank was conducted. A picture of the manifold used for this series of tests is shown in Figure 2. The results of these tests are shown in Figures 8 through 10. Surface velocities normal to the manifold were measured for several positions along a line parallel to the intersection of the water surface and a vertical plane formed by the axis of the air manifold and a vertical line. The results of these tests confirm the previous indication that the depth effect is most pronounced in water less than 10 feet in depth for multi-jet configurations for the spacing tested. As a result of these findings, an extrapolation of the tank test data to river depths was considered feasible.

The effectiveness of a pneumatic barrier in a current could not be determined in the laboratory water tank facility; therefore, this phase of the program was performed in the Buffalo River. After an examination of the data from the tank tests, as well as data on river discharge, it was decided to test the 1-mm nozzle at one-foot spacing and the 2-mm nozzle at 1- and 2-foot spacings. The configuration of a 1-mm nozzle at 2-foot spacing was not considered in the river test program since the velocities generated in the tank test were too low for river conditions.

Currents in the Buffalo River may reach a velocity of 5 feet per second for short periods of time during the spring of the year. However, for most of the time the river current is much less than this value. For example, during most of the summer a velocity of 0.5 foot per second is normal. From an examination of available river flow data supplied by the U.S. Army Corps of Engineers it is clear that if the surface current generated by a pneumatic barrier was such as to create a stationary stagnation zone in a 1.5 fps river current, the pneumatic barrier could be effective for a large portion of a year. In fact, the statistical flow frequency data provided for the river indicate that it is possible to conclude that a current of 1.5 fps would be exceeded by the seven-day average of the current only once in ten years. If, however, one considers the maximum average one-day flows, it is almost certain that during any year the 1.5 fps current will be exceeded on some one day. As a result of these facts, a year-round effectiveness cannot be assumed, if one designs a barrier to operate in a 1.5 fps current. However, such a barrier will be effective for a very high percentage of time throughout the year.

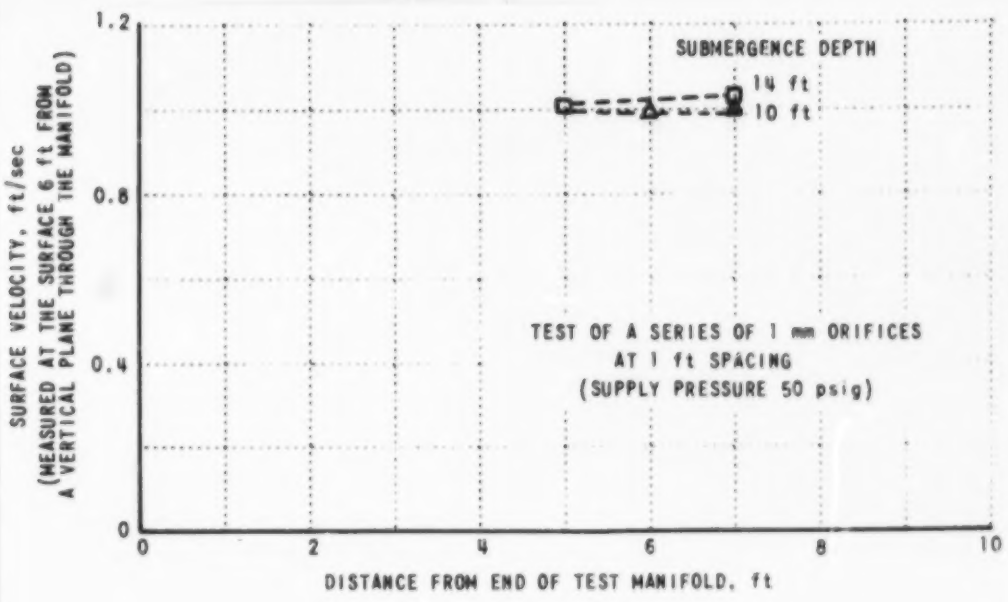


Figure 8 DISTRIBUTION OF SURFACE VELOCITIES NORMAL TO MANIFOLD.

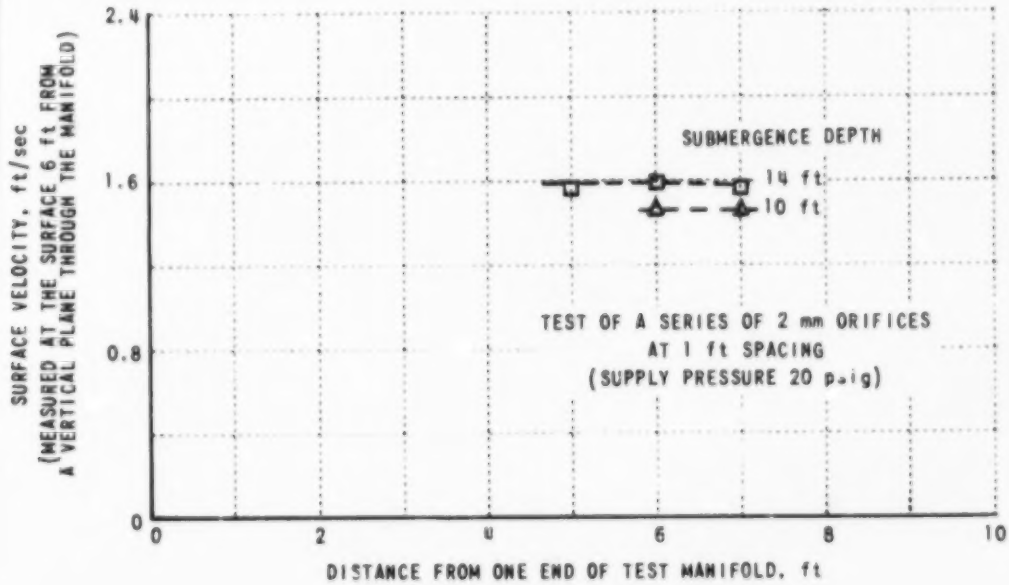


Figure 9 DISTRIBUTION OF SURFACE VELOCITIES NORMAL TO MANIFOLD

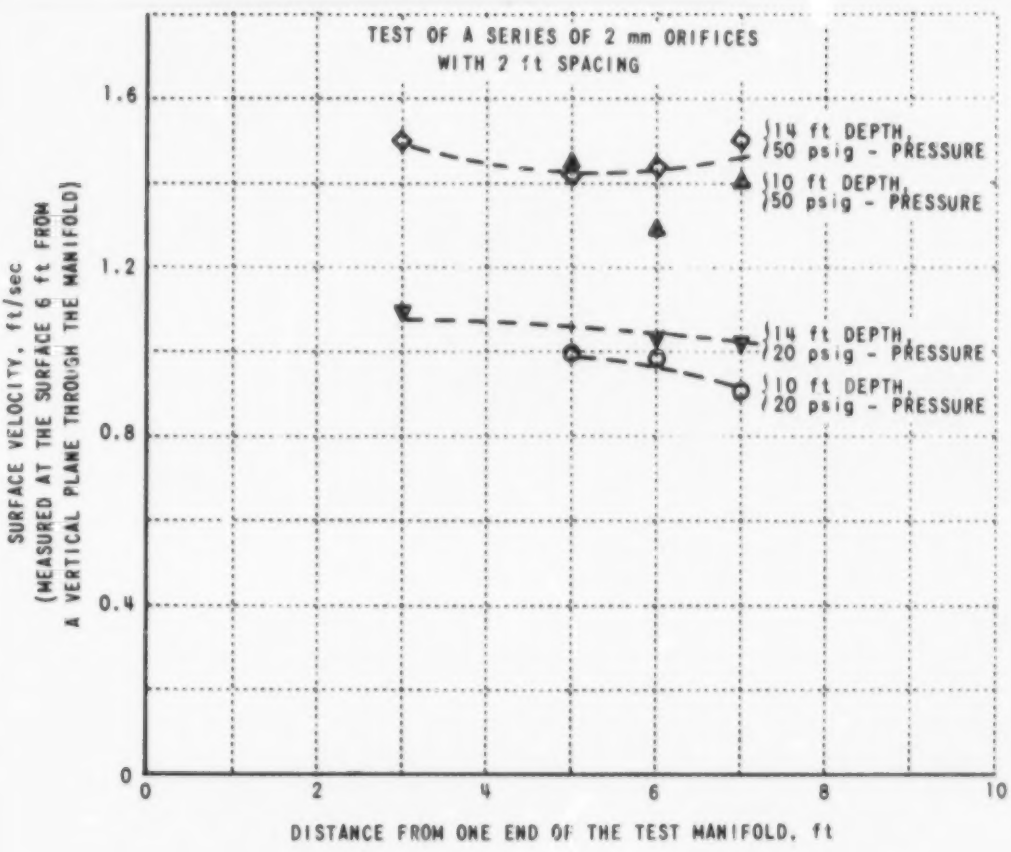


Figure 10 DISTRIBUTION OF SURFACE VELOCITIES NORMAL TO MANIFOLD

DESIGN OF THE PNEUMATIC BARRIER

SELECTION OF THE PNEUMATIC BARRIER SITE

The selection of a site for installation of the experimental pneumatic barrier in the Buffalo River was dependent on a number of factors, some of which were not directly related to barrier performance. Among the more pertinent considerations were: (1) availability of an adequate supply of electrical power, (2) easy access to site for maintenance operations, (3) site near juncture of Buffalo River and Lake Erie so that maximum amount of oil could be prevented from entering the lake, (4) favorable position relative to prevailing winds, and (5) availability of vertical bulkheads at the edge of the river upon which the ends of the barrier could be attached. Of these conditions, only Item (5) requires further explanation. For the experimental program, it was desired to minimize any problems that might occur from leakage of oil around the ends of the pneumatic barrier. From water tank tests, it was clear that if a barrier was terminated near a vertical wall in ten or more feet of water, the currents generated near the wall formed an effective seal against end losses. Therefore, since such a solution to the end loss problem was simple and effective, the requirement for a vertical boundary wall for the river channel was incorporated as an important pneumatic barrier site selection consideration.

Although the question of the distribution of surface oil along the river was not initially considered in the site selection process, it has become clear from a post facto judgment that such a distribution should be considered as an important parameter for site selection.

The location of the site selected, which satisfies most of the conditions stated above, is shown in Figure 11. A closer view of the immediate area around the barrier site is shown in Figure 12. At the site selected the Buffalo River is approximately two hundred feet wide. The shape of the channel is shown in a cross-sectional view in Figure 13. The water depth in the river was usually about twenty-eight feet during the period of testing. The contours of various sections of the river were derived from U.S. Coast Guard soundings obtained in September 1968. The composition of the river bed, as verified from bottom specimens, consists of hard pan clay across most of the channel. Near the shores a deposit of oil laden muck or silt was found to overlay the clay. The fact that most of the river bed at the Michigan Avenue site was clay simplified some design considerations since the question of the barrier burying itself in silt was no longer of importance.

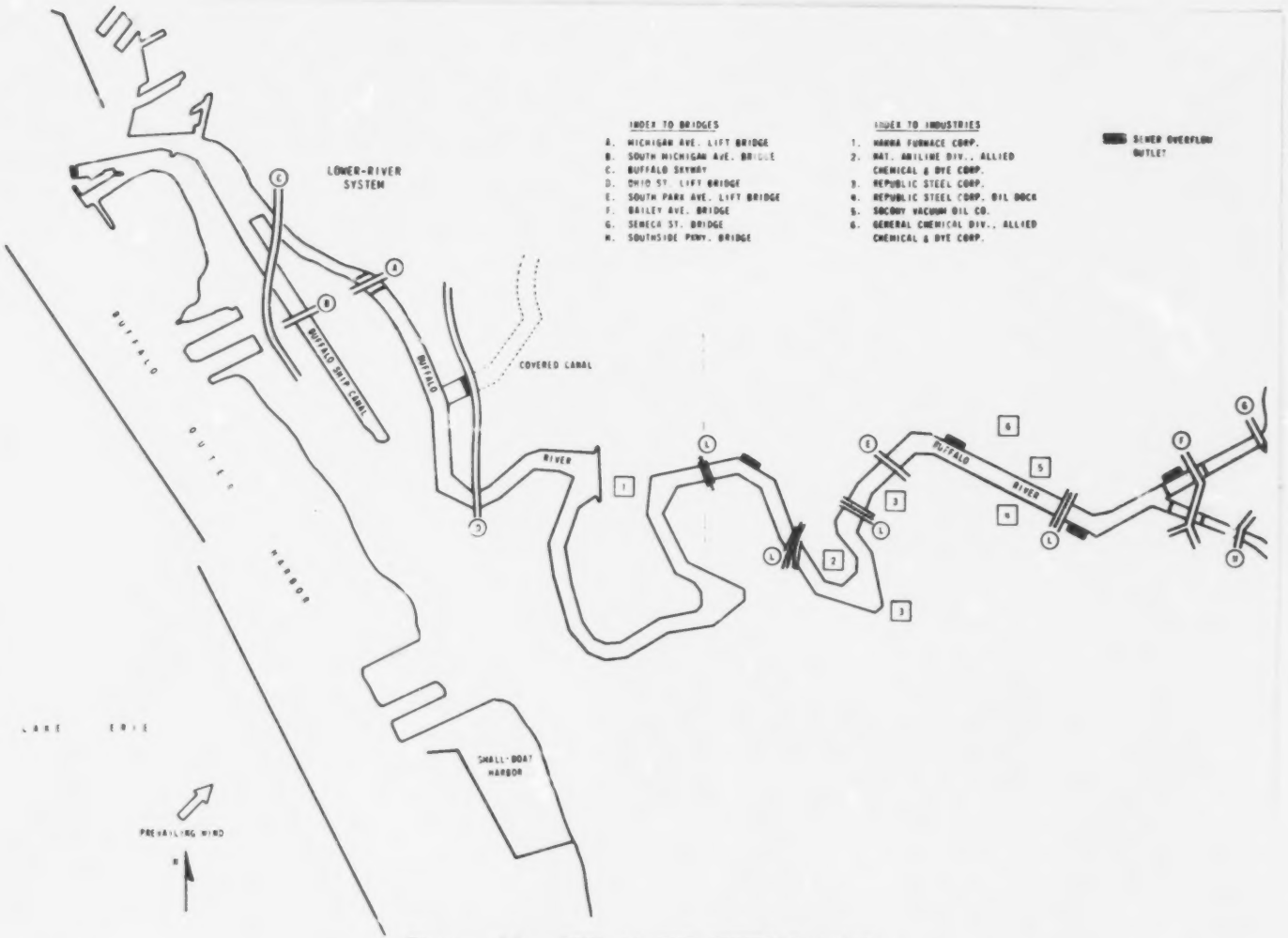

INDEX TO BRIDGES
A. MICHIGAN AVE. LIFT BRIDGE
B. SOUTH MICHIGAN AVE. BRIDGE
C. BUFFALO SKYWAY
D. OHIO ST. LIFT BRIDGE
E. SOUTH PARK AVE. LIFT BRIDGE
F. BAILEY AVE. BRIDGE
G. SENECA ST. BRIDGE
H. SOUTHSIDE PKWY. BRIDGE
INDEX TO INDUSTRIES
1. HANNA FURNACE CORP.
2. NAT. ANILINE DIV., ALLIED CHEMICAL & DYE CORP.
3. REPUBLIC STEEL CORP.
4. REPUBLIC STEEL CORP. OIL DOCK
5. SOCONY VACUUM OIL CO.
6. GENERAL CHEMICAL DIV., ALLIED CHEMICAL & DYE CORP.
SEWER OVERFLOW OUTLET
LOWER-RIVER SYSTEM
BUFFALO OUTER HARBOR
BUFFALO SHIP CANAL
BUFFALO RIVER
COVERED LAGAL
LAKE ERIE
SMALL-BOAT HARBOR
PREVAILING WIND

Figure 11 MAP OF THE BUFFALO RIVER

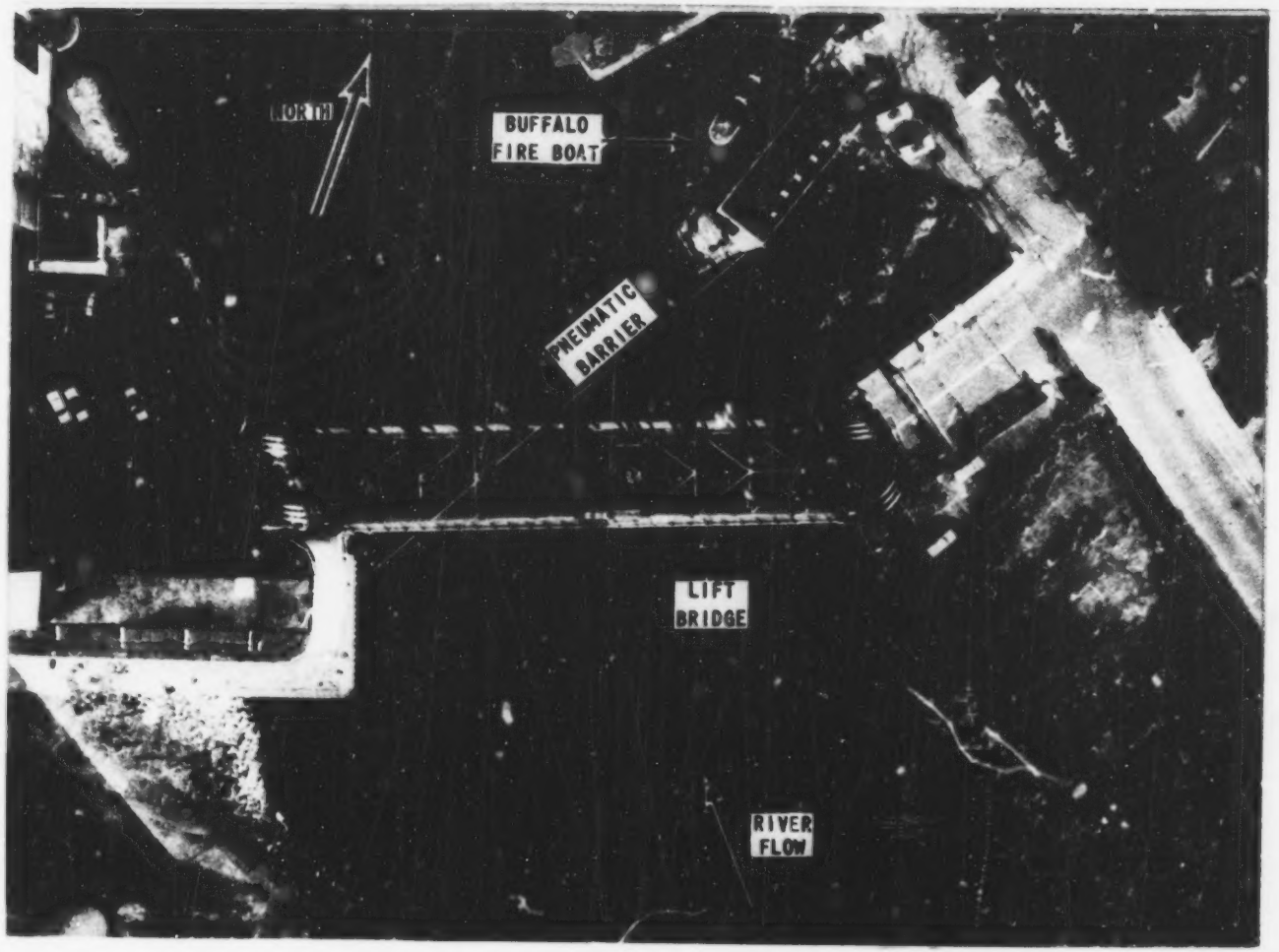


Figure 12 AERIAL VIEW OF PNEUMATIC BARRIER SITE AT MICHIGAN AVENUE LIFT BRIDGE

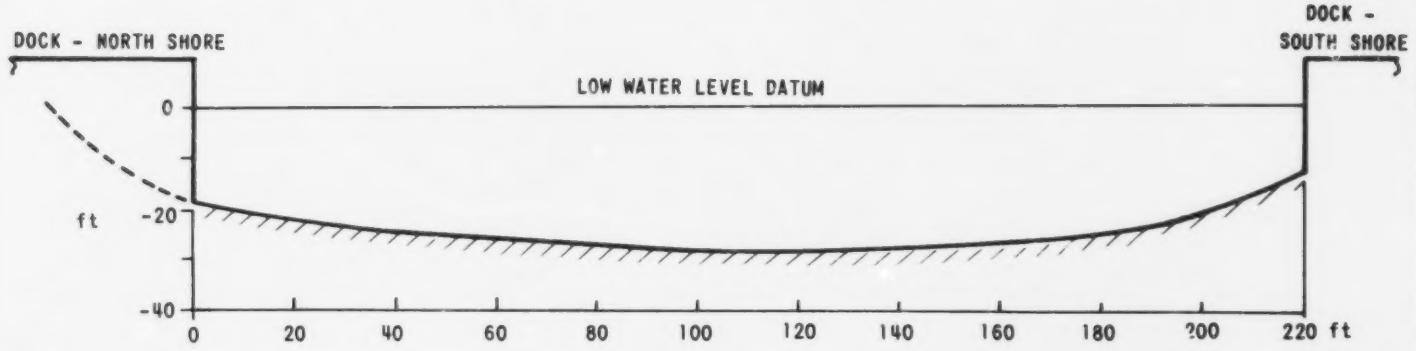


Figure 13 BUFFALO RIVER BED CONTOUR - SOUTH MICHIGAN AVENUE BRIDGE SITE

COMPONENTS OF THE PNEUMATIC BARRIER SYSTEM

Air Manifold

The site location as noted above can be seen in Figure 12. The path or approximate location of the pneumatic barrier is shown by the dashed line in this figure. The length of the barrier used along this path was approximately 250 feet. Although only a single air tube or manifold is necessary for the operation of a pneumatic barrier, two additional tubes were used in the experimental design to provide ease of maintenance. These additional tubes were placed one on each side of the central air manifold and were used solely for the purpose of raising and lowering the barrier. For example, when the outside tubes were filled with water, the system sank; when the water was purged and these tubes filled with air, the system floated. In the construction of the barrier, three-inch-diameter polyethelene tubes were used. This material was chosen since it is very inert to corrosive chemicals, relatively flexible in long lengths and capable of withstanding the pressures anticipated in the system.

Anchorage of the Air Manifold

To ensure that the system would stay submerged when air was injected in the central manifold, concrete anchor blocks were placed along the length of the three-tube system. In addition, since high river currents can be expected at certain times of the year, drag cables were connected to the concrete blocks so that the force exerted by the flowing water could be taken up by the steel cables rather than by connections to the plastic tubing. A picture of the configuration showing the polyethelene tubes, concrete blocks and cables is shown in Figure 14. A schematic diagram of the air barrier system placed in the Buffalo River is shown in Figure 15.

The detailed construction of the anchorage mechanism is shown in Figure 16. On the north shore (Figure 16) two winches were used -- one to adjust the tension on the cables supporting the manifold system and the other to adjust the position of the barrier on the river bottom. The winch on the south shore anchorage (Figure 16) is used only for positioning the manifold system. The actual connection of the manifold cable system to the shore bulkheads is shown schematically in Figure 15. It may be noted that the shore anchorage system was initially designed to insure ease of maintenance during the experimental program and as such is more sophisticated than would be required for a permanent installation.

Nozzle Construction and Configuration

Since it was desirable to use a number of nozzle configurations in the river test program, it was decided to use the nozzles that were designed and developed for the water tank tests. These nozzles were made from #1032 stainless steel phillips-head machine screws wherein

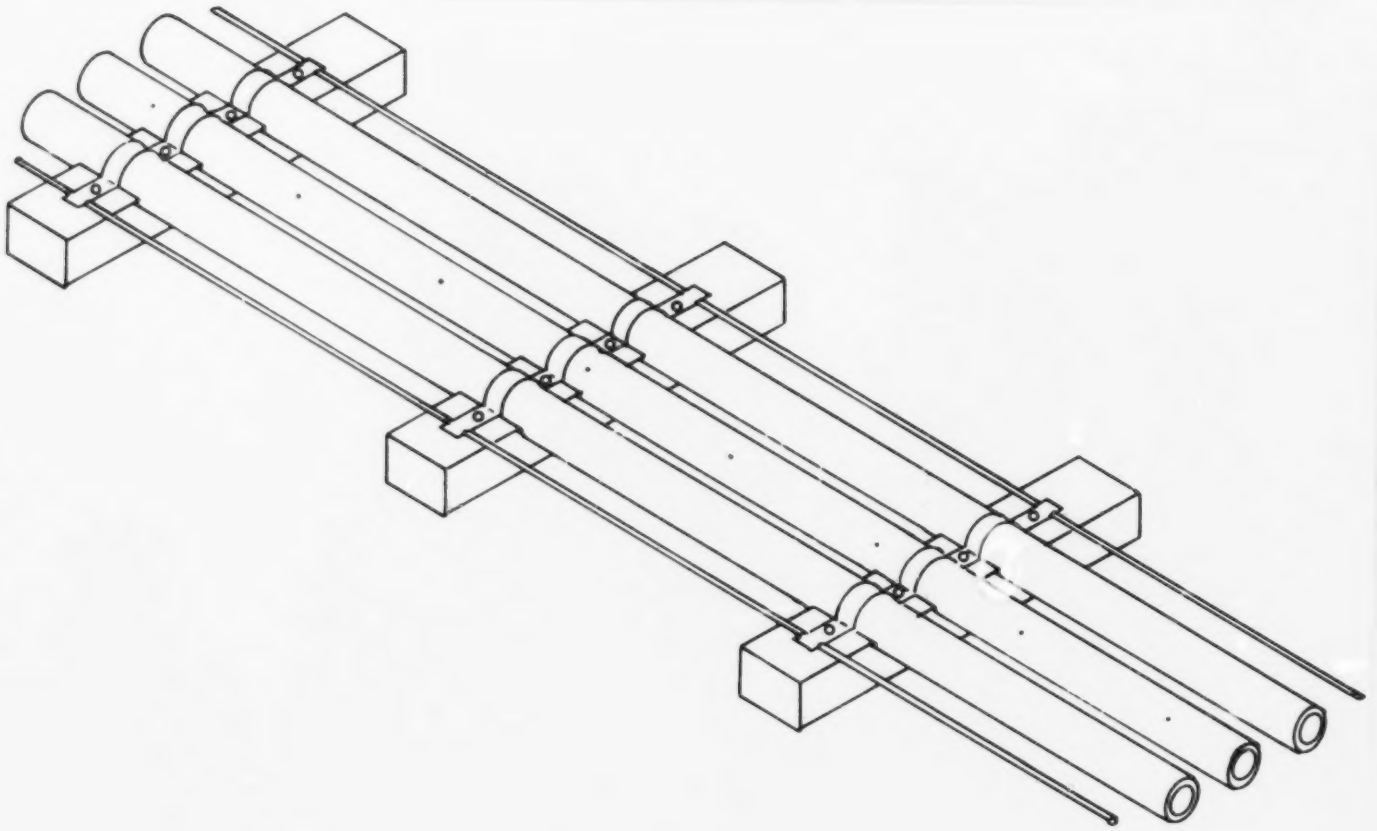


Figure 14 PNEUMATIC BARRIER. TUBES. ANCHOR BLOCKS AND CABLES

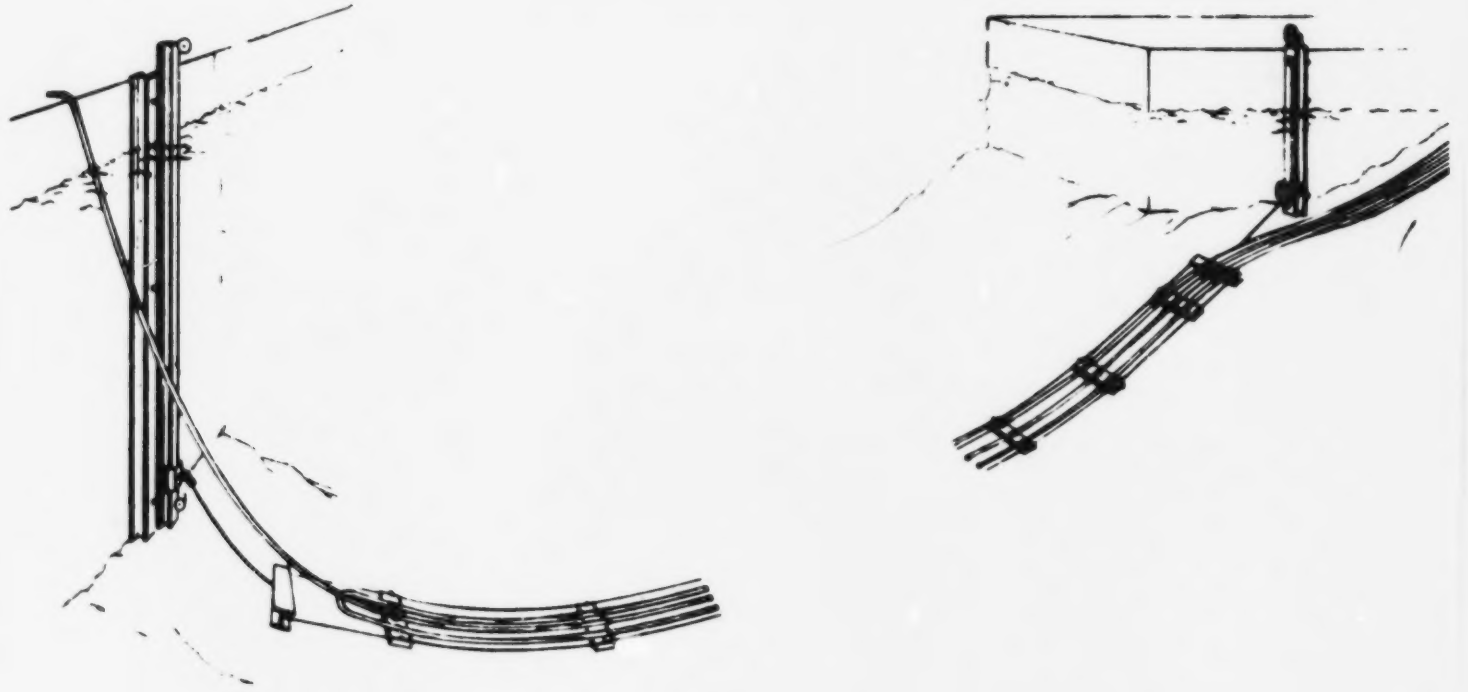


Figure 15 SCHEMATIC OF PNEUMATIC BARRIER IN BUFFALO RIVER

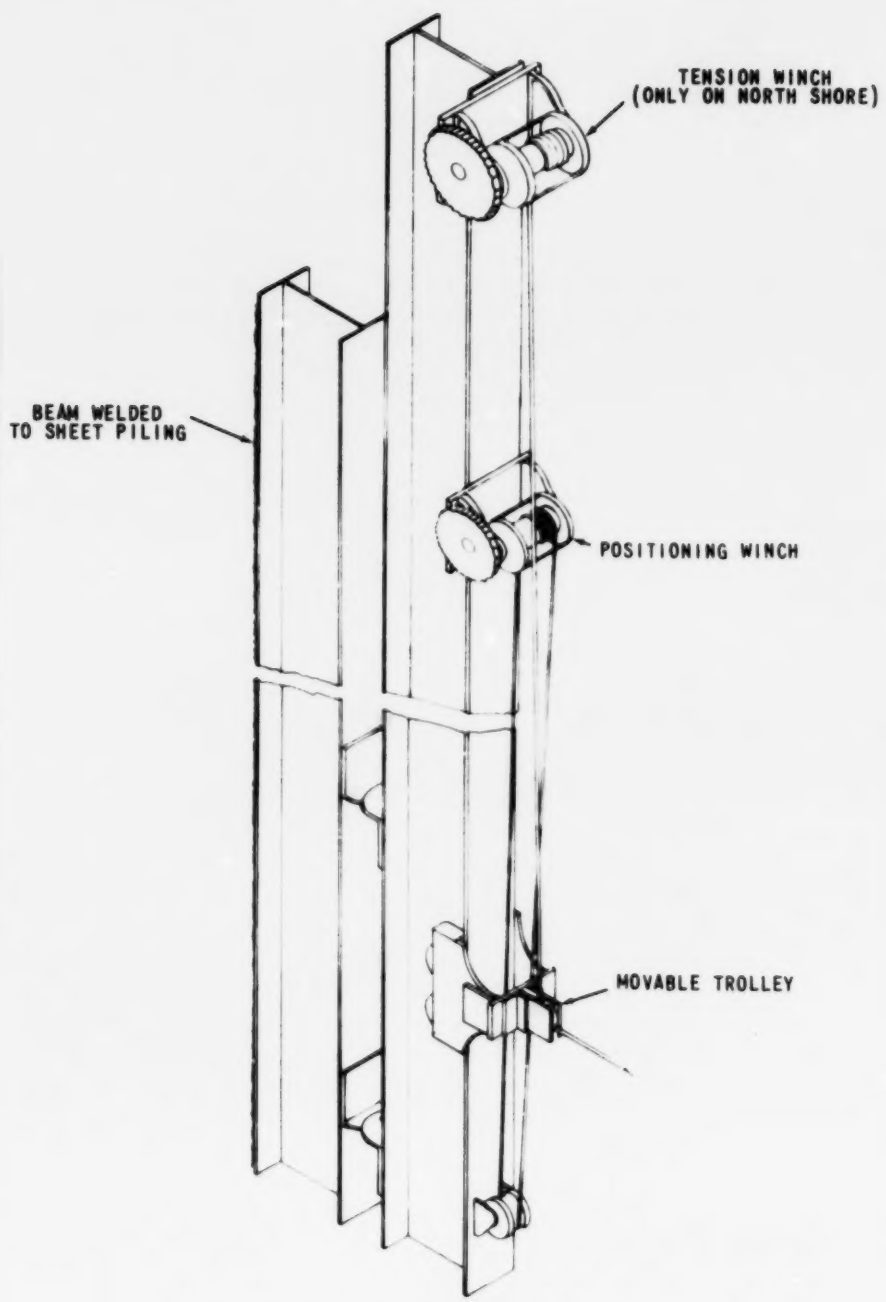


Figure 16 PNEUMATIC BARRIER SHORE ANCHOR

holes corresponding to the desired jet diameter were drilled. A photograph of two screws, one having a one-millimeter hole and the other a two-millimeter hole, is shown in Figure 17.

The air barrier system was operated for various periods of time from a few hours to a few days. At the end of a test run the air supply was shut off completely. Start-up of the system was accomplished by reopening the air supply valve. At no time during the experimental program was there any evidence of fouling of the nozzle. In fact, before each nozzle change the nozzles were individually inspected for signs of plugging. No instance of plugging was found for either the one- or two-millimeter nozzles.

The pattern of holes selected for the test of the pneumatic barrier was dictated by the results of the tests in the CAL water tank. As noted previously, three configurations were used; namely, a 2-millimeter diameter hole with a two-foot spacing, a 2-millimeter hole with a one-foot spacing and a 1-millimeter hole with a one-foot spacing. Holes with a diameter equal to the root diameter of a #1032 machine screw were drilled at one-foot intervals along the length of the central air manifold. The #1032 screws used for nozzles were then threaded into these holes. Any one of the above nozzle configurations could be generated through use of the appropriate distribution of screws with and without holes. A change in configuration was accomplished readily by floating the manifold to the surface and changing the nozzle blank pattern.

Air Supply

In order to provide sufficient air over a range of supply pressures for the configurations noted above, two 600-scfm 150-hp portable rotary electric air compressors were used. These compressors were connected to the system so that either or both could be used as desired during the test program. For the majority of the test program only one compressor was used. However, for certain combinations of river current and nozzle configurations, two compressors were used. The size of a compressor to be used in a permanent installation will be discussed in a later section of this report.

It was initially thought that the generation of a sonic exit velocity in a nozzle would be necessary, neglecting the effect of a variation in density with pressure along the manifold, to generate a uniform mass flow through each nozzle. Observations, however, showed that this condition was not necessary. In fact, it became clear from the test observations that once the supply pressure exceeded the maximum hydrostatic pressure in the river by 5 psig a uniform air distribution was obtained.

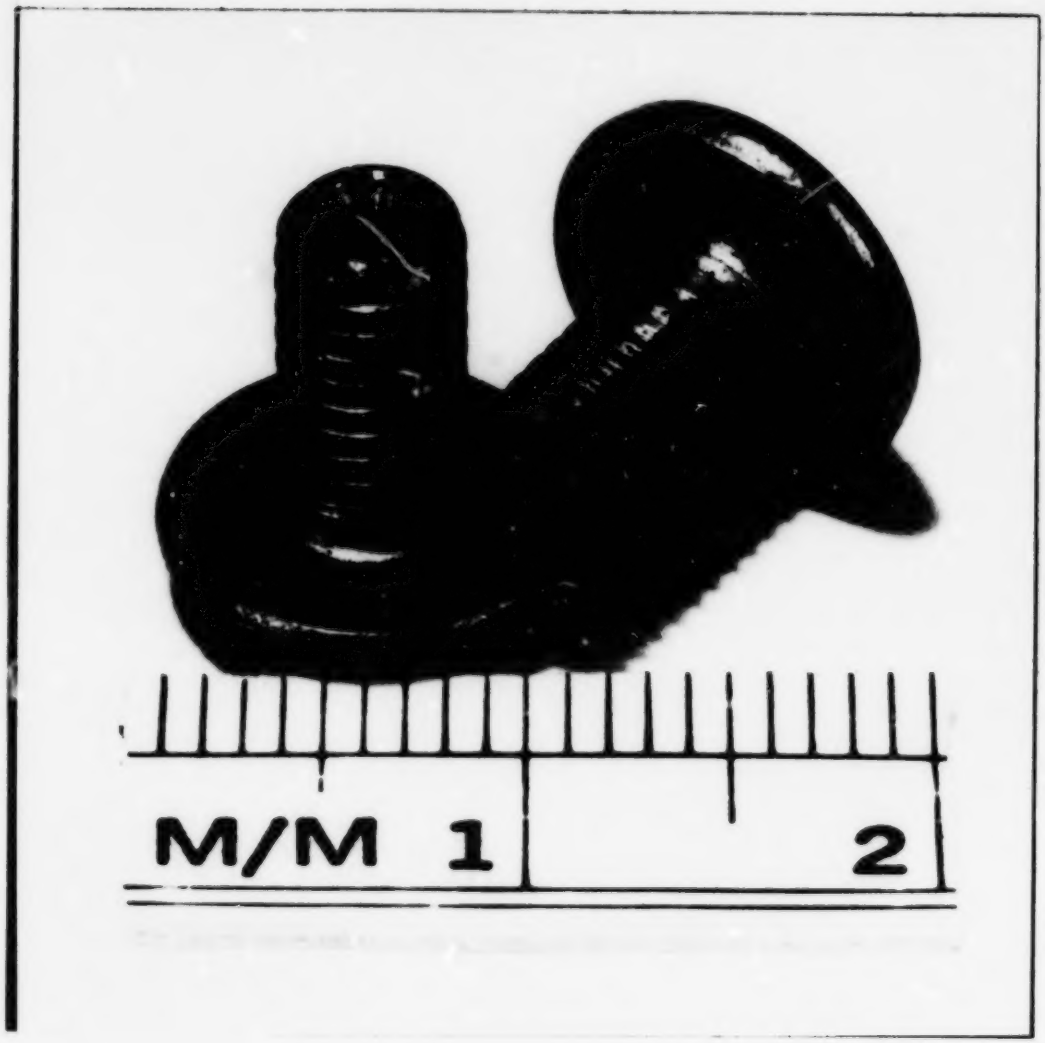


Figure 17 1 mm AND 2 mm NOZZLES

RIVER TEST PROGRAM

TEST MEASUREMENTS

On completion of the installation of the pneumatic barrier in the Buffalo River, the program to test the effectiveness of this device in a current was started. Since it was not feasible to make detailed velocity surveys over the surface of the river, measurements of velocity were limited to points directly below the Michigan Avenue Bridge. Most measurements of velocity were made from a single station on the bridge surface. The position of this station was chosen so that measurements of river velocity would not be influenced by currents generated by the pneumatic barrier. In addition to measurements of surface velocities and river profiles directly below a bridge station, the position of the zone of turbulent activity of the barrier and the position of the oil slick formed were noted. Measurements of river velocity, magnitude as well as direction, were made with a Savonius current meter. This instrument was ideally suited to measurements of the low river currents existing for much of the time during late spring and early summer.

The Savonius meter that was used to measure river current had a stated accuracy of ± 0.03 fps for velocities less than 1.5 fps. It should be noted, however, that even though the instrument was capable of measuring the average value of the river current very accurately, it is possible for these average values to vary from minute to minute due to turbulent velocity fluctuation within the river. A detailed error analysis was not carried out during the series of tests but an attempt was made to ensure repeatability of river velocity data. Average velocity measurements were recorded at one minute intervals throughout the period of a test, which usually lasted between ten and fifteen minutes. From these readings a straight arithmetic average was taken of the velocity data to obtain a test average. If the series of velocity measurements had a variation of more than 0.1 fps, the test was discounted.

During the test program, the surface positions of the barrier and slick positions were noted for various orifice configurations as well as various values of the system parameters. The system parameters of importance were mass flow rate of air, supply pressure, wind velocity and river velocity. In the course of the analysis it is instructive to examine the difference, Δ , between the oil slick location and the upstream edge of the turbulent zone as a function of system parameters. The reason for this choice is that Δ can be directly related to the condition in which an oil slick formed on the upcurrent side of the barrier is no longer totally restrained by the barrier. When this condition occurs one finds that streaks of oil appear on the downcurrent side of the barrier. The distance between streaks may vary laterally from a few feet up to twenty feet. It may be emphasized that during this process, only a portion of the oil slick is no longer retained.

TEST DATA ANALYSIS

As a first step in the analysis of the data, consider the effect of supply pressure on the operational characteristics of the barrier. In Figure 18, Δ is plotted as a function of supply pressure for a fixed volumetric air flow rate. From an examination of points with current velocity, 0.2 fps in Figure 18a, 0.2 - 0.3 in Figure 18b, and 0.4 fps in Figure 18c, it is clear that pressure has virtually no effect on barrier operation for these low velocities. For velocities of 0.6 and 0.7 fps, the data from Figure 18c provide an indication that there is a beneficial effect of an increase in pressure. The conclusion to be drawn from these data is that for velocities less than 1/2 foot per second, there is a negligible benefit derived from an increase in pressure in the system. For velocities greater than 1/2 foot per second, there is an indication of a slightly beneficial effect. However, to strengthen this indication, additional high-velocity data would be required.

Consider next the question of the effect of a change in volume air flow rate on Δ for a constant pressure. Figure 19 is a plot of Δ vs. scfm/ft for a constant pressure. In Figure 19a (where the supply pressure is 30 psig), note that for 3.75 scfm/ft, Δ increases as the river current decreases. From this behavior, one would conjecture that the value of Δ for 0.3 fps at 3.75 scfm/ft would be greater than or equal to the value of Δ for 0.5 fps With this information in mind, one can observe a not insignificant change of Δ vs. scfm/ft for a velocity of 0.3 fps. In Figure 19b the test conditions differ from those of Figure 19a in that the supply pressure was increased to 40 psig from 30 psig. The increase of Δ with scfm in Figure 19b of 0.4 fps is not as great as that seen for practically the same velocity in Figure 19a. Therefore, from the data presented in Figure 19a and 19b, one would infer that as the pressure increases, the effectiveness of an increase in volumetric supply of air decreases. These conclusions are applicable to water velocities less than a foot per second. Additional data would be required to qualify these conclusions further as well as to extend them to higher velocities.

Although primary interest is, of necessity, focused on the behavior of barriers in restraining oil, it is of interest to investigate the behavior of the air-bubble pattern itself as a function of river current. Therefore, plots have been made of Δ *--the distance from the mean position of the bubble pattern in a current to the mean position of the bubble pattern in virtually zero flow. In Figure 20, plots a, b, c, and d show Δ * vs. scfm/ft at fixed pressures. A cross plot of these data could be made to show the effect of a change in pressure at constant volume on barrier position. From a and b, it is evident that the Δ * is virtually insensitive to a change in volumetric rates for constant pressure for velocities less than 1 fps. One would expect this behavior to be true as the pressure is increased for the same restriction on velocity; however, the data necessary to confirm this are not available at this time. Also, by cross plotting the data; that is,

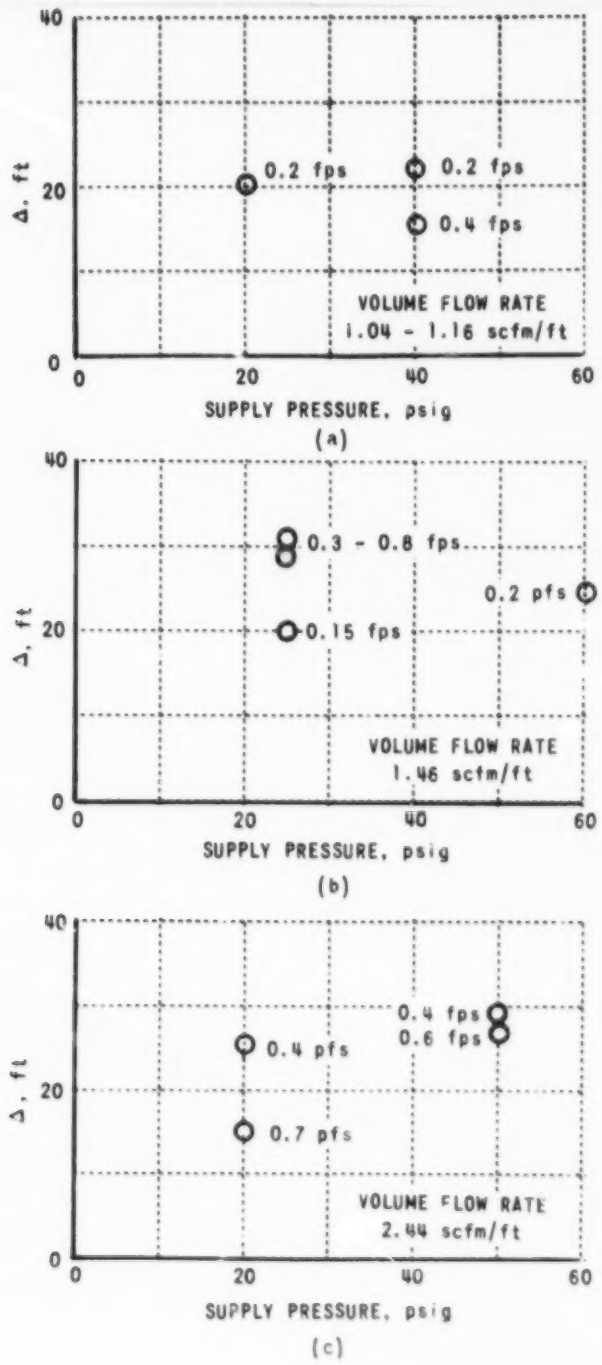
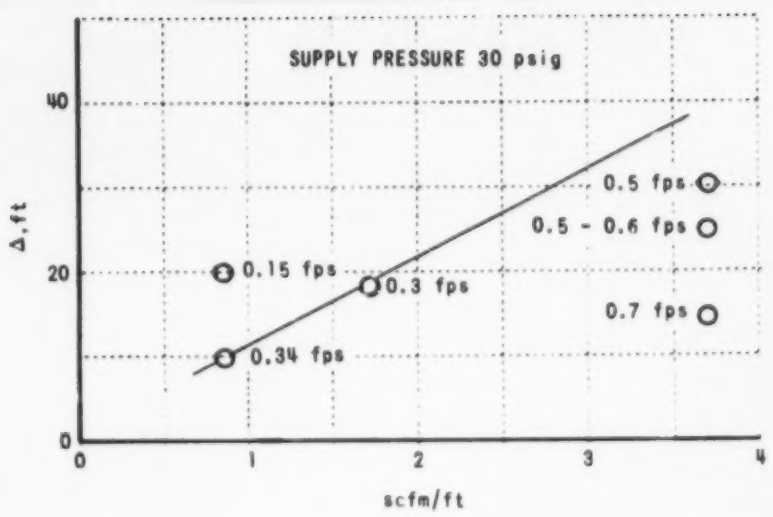
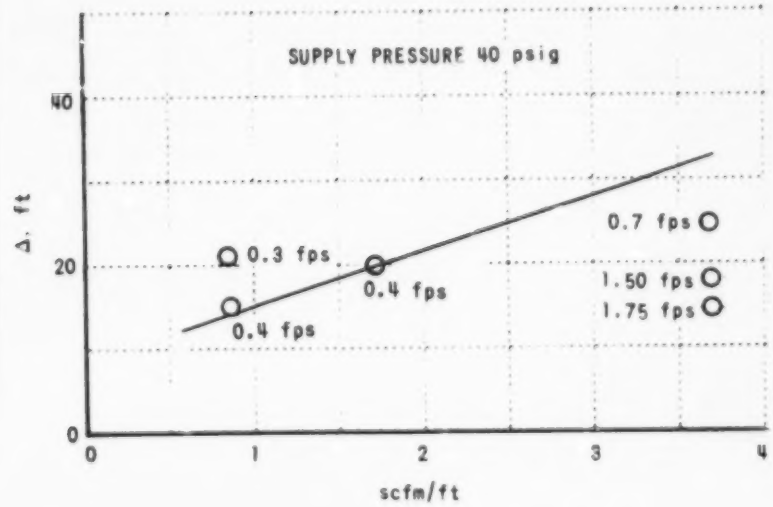


Figure 18 THE EFFECT OF SUPPLY PRESSURE ON Δ



(a)



(b)

Figure 19 EFFECT OF VOLUMETRIC FLOW RATE ON Δ

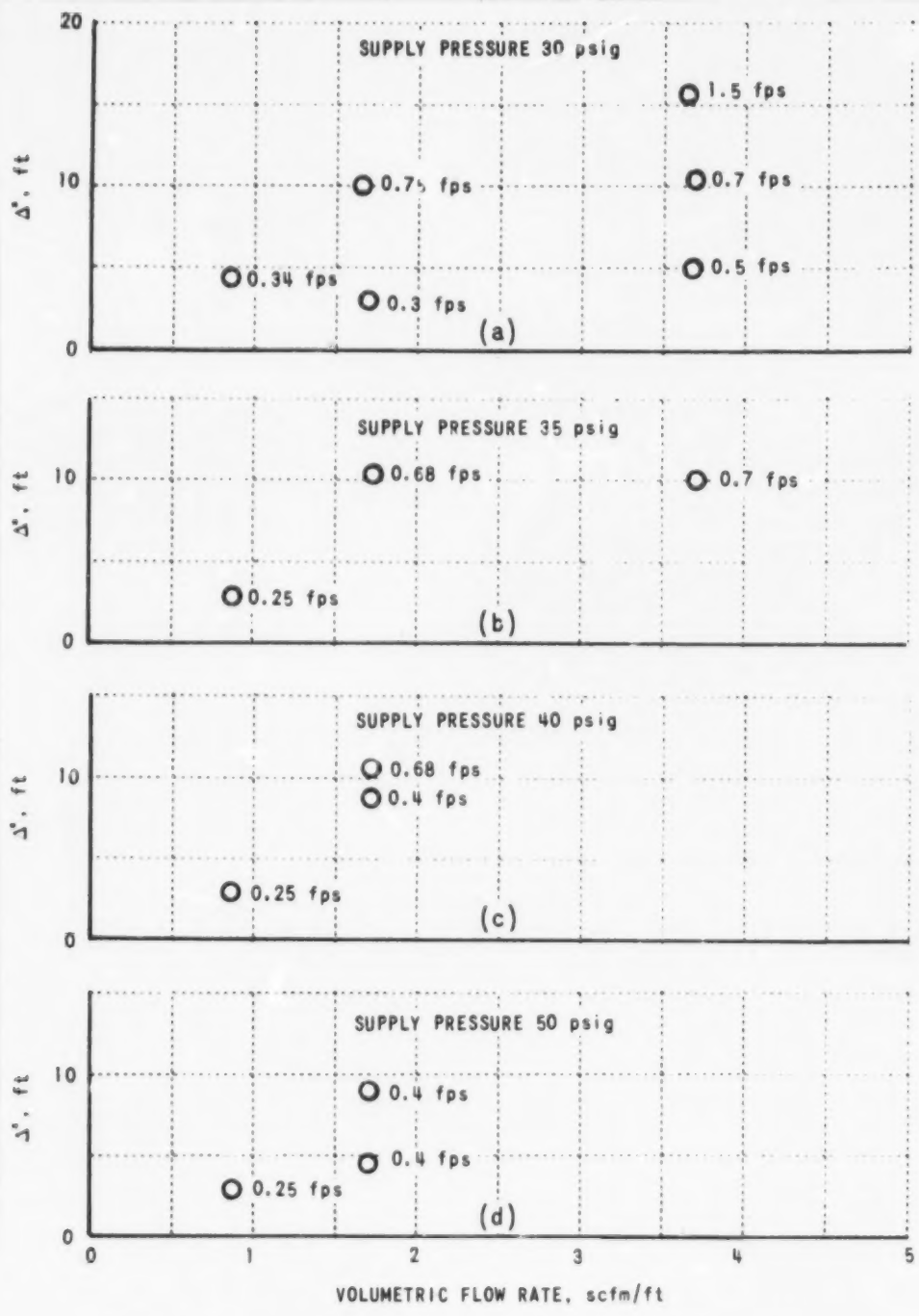


Figure 20 EFFECT OF THE VOLUMETRIC FLOW RATE ON Δ° FOR VARIOUS SUPPLY PRESSURES

Δ * vs. pressure for fixed volume, one can also conclude that for currents less than 1 fps, Δ * varies very little with pressure.

Studying the results in Figure 20, it may be concluded that for currents of 1 fps or less, the mean position of the surface turbulent zone varies very little with a change in supply pressure or volumetric rate. The principal cause for any change in Δ * is river velocity, as may be seen in Figure 21.

Although little data was available for river currents greater than 1 fps, some data were obtained for a velocity of 1.5 - 1.75 fps. The barrier operated satisfactorily at these higher velocities. However, these conditions did not persist long enough for a series of measurements to be taken.

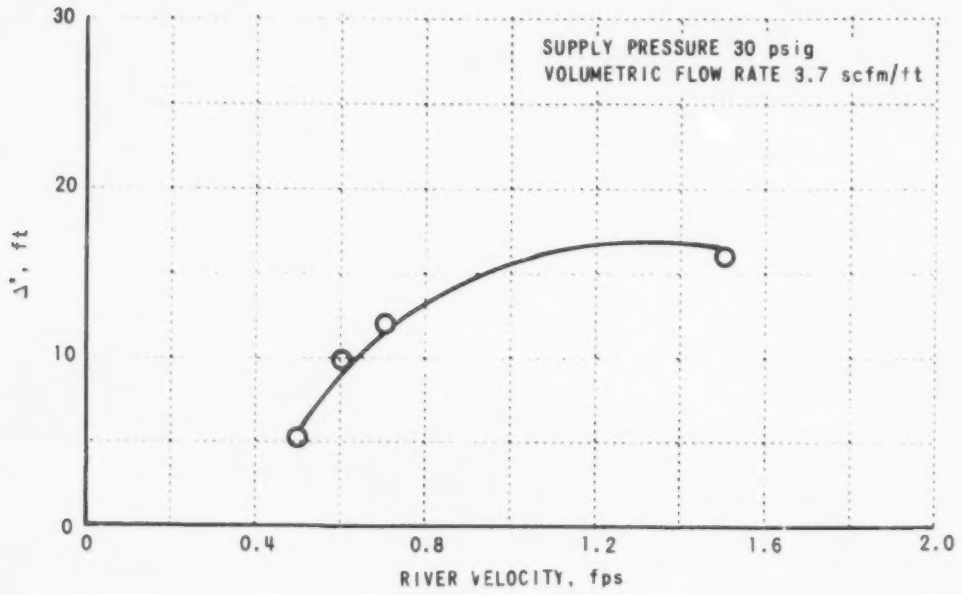


Figure 21 THE EFFECT OF RIVER VELOCITY ON Δ^*

LIMITATIONS OF THE INSTALLED PNEUMATIC BARRIER SYSTEM

During the period of testing of the pneumatic barrier, the operational characteristics of this device were observed quite closely. After it became apparent that the expected quantities of oil were not being accumulated, hypotheses for this situation were conjectured. First, the river current changes direction frequently during the day; and second, the amount of surface oil observed near the Michigan Avenue bridge is not large. Both of these hypotheses have now been verified.

For a single pneumatic barrier to operate efficiently in a current, the current direction must remain constant long enough to permit the accumulation of a sufficient quantity of oil for effective skimming. The variability of the current direction in the Buffalo River can be a dominant factor on the operation of a single pneumatic barrier. The mechanism for the reversal of current direction in the Buffalo River is the variation of the level of Lake Erie due to wind variations. A plot of the magnitude and direction of the surface river current for a day in June is shown in Figure 22. An additional plot showing river behavior on a typical day is shown in Figure 23. This latter plot consists of a series of velocity profiles taken at various times during a particular day. From Figure 22, one may note that the river current may change direction within as short a time as thirty minutes. However, experience has indicated that generally unidirectional flow will be found to persist for a few hours.

The directional variability of river current was one reason why relatively little oil was accumulated at the barrier site. While the current is in one direction, the barrier is very effective in stopping the oil. However, if the direction of river flow changes, the accumulated oil will be carried away by the reversed current. The solution to this problem may be through the use of two barriers, each activated independently, depending on current direction.

The fact that relatively little oil was collected was directly dependent on the amount of oil present on the surface at the Michigan Avenue site. Only surface streaks of oil were found and, even though these were stopped, there was only very little surface oil accumulated during the unidirectional period of flow. If one conjectured a unidirectional current for a longer period of time, it is questionable whether an amount of oil could be accumulated which could be effectively collected. The amount of oil on the river surface as a function of position in the river was investigated; the results are contained in Reference 14.

WIND EFFECT ON BARRIER PERFORMANCE

Until this point, very little has been mentioned of the effect of wind velocity on the behavior of the slick near the barrier. The reasons for this are threefold. First, during the time of most tests, the wind velocity was relatively low (10 mph). Second, the prevailing wind is

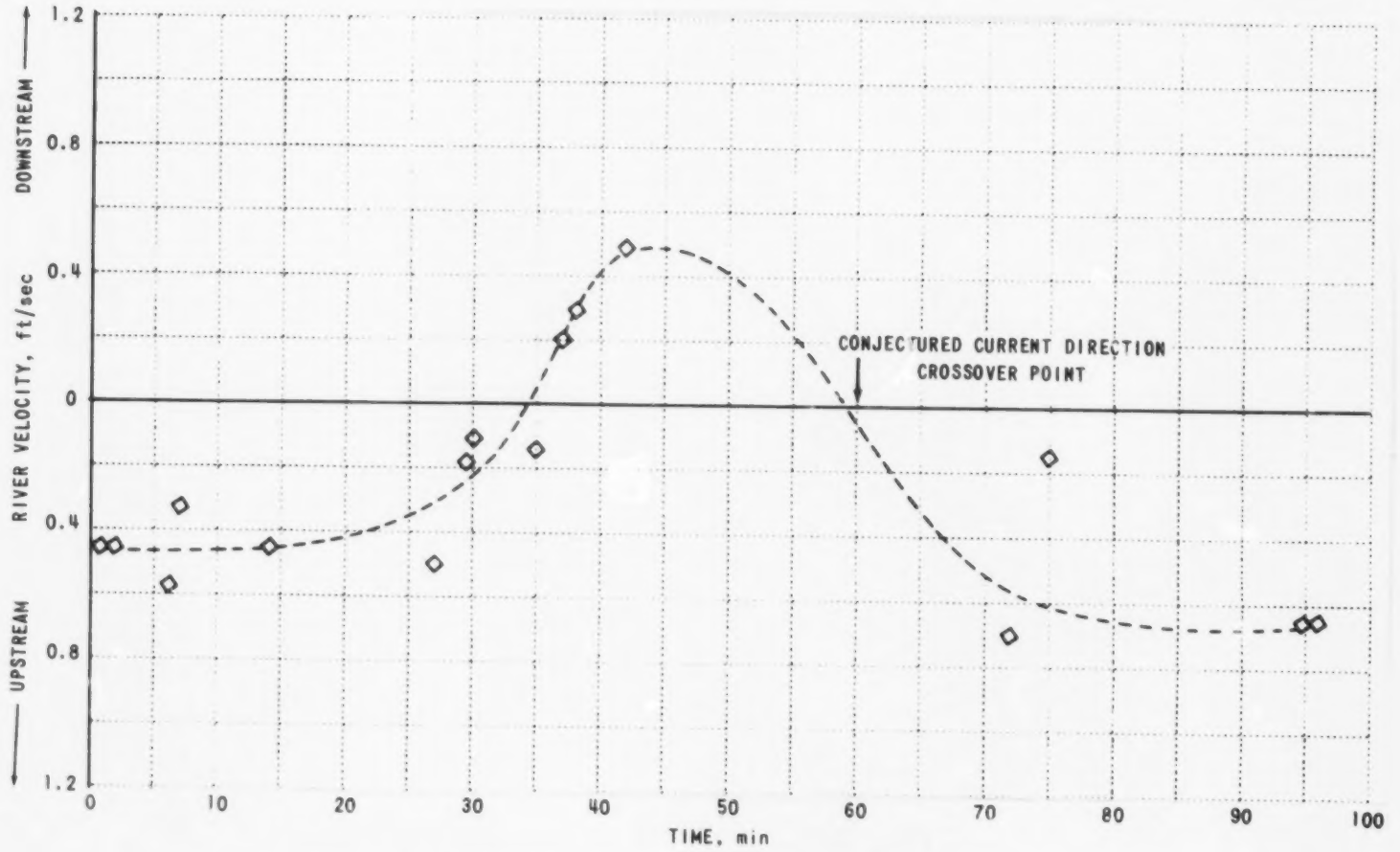


Figure 22 VARIATION OF SURFACE VELOCITY ON ONE DAY

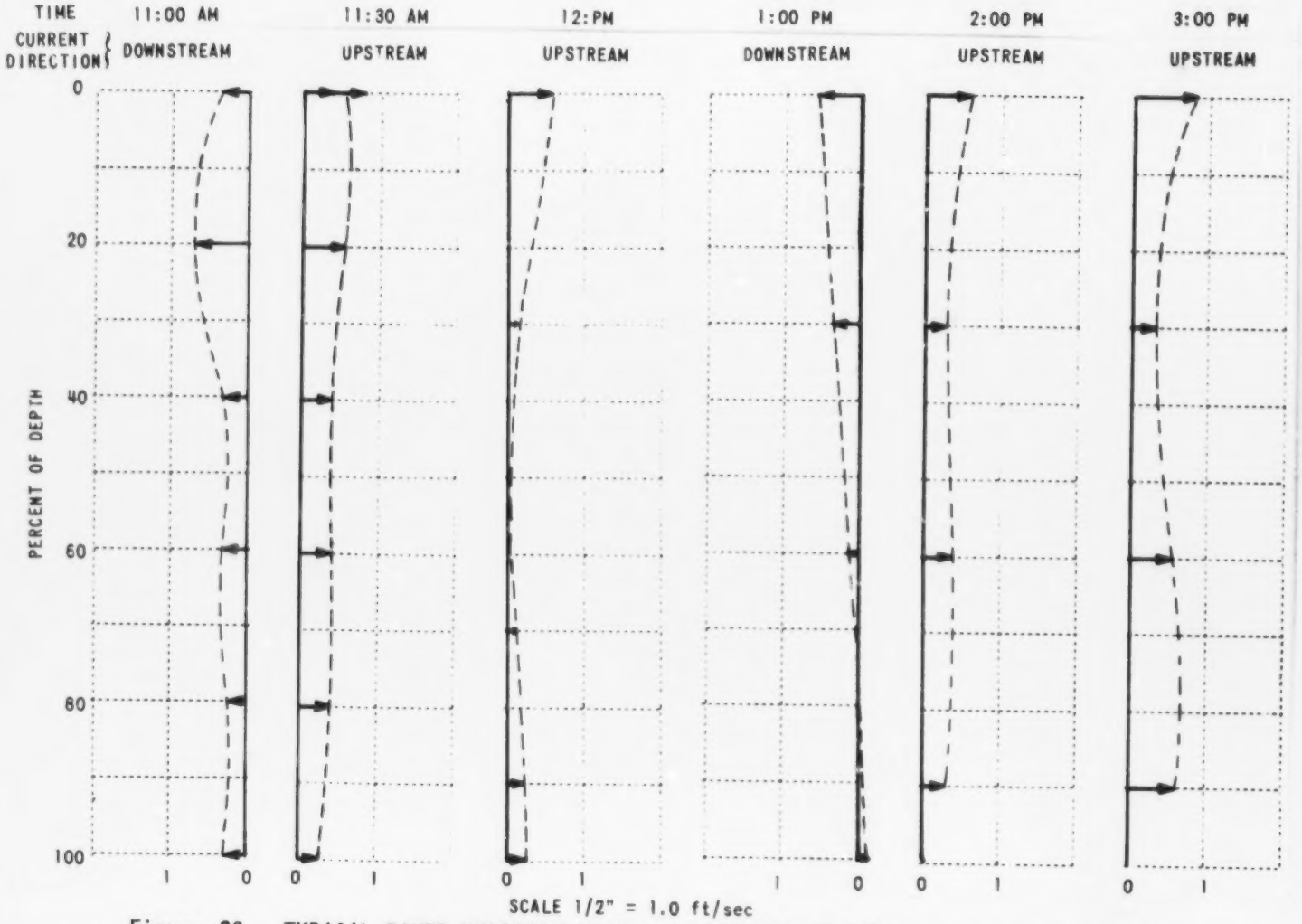


Figure 23 TYPICAL RIVER VELOCITY PROFILES OBTAINED AT VARIOUS TIMES ON ONE DAY

almost at right angles to the current direction at the location of the air barrier. Therefore, its primary effect would be to move any accumulated oil toward shore. Third, the area in the immediate vicinity of the barrier is somewhat sheltered by surrounding buildings.

It may be expected that the greatest detrimental effect of wind on barrier performance would be when the wind was blowing in the same direction as the river current. One might conjecture that for such a case the wind, if its velocity were high enough, would move the accumulated oil nearer to or through the turbulent zone above the barrier. Such a conjecture cannot be answered entirely from the test data available since only a single instance of such an adverse wind existed. For this case the wind had a speed of 10 mph. There was no perceptible effect on the position of the accumulated oil slick due to this wind. The behavior of the accumulated oils subject to winds of higher speeds cannot be answered from the present test data.

ADDITIONAL LABORATORY EXPERIMENTS

INTRODUCTION

Following the completion of the river test phase of the program, it became obvious that if the evaluation of a pneumatic barrier was to be continued in more detail and for higher current conditions, it would be necessary to develop a laboratory facility in which to conduct the experiments. The experimental facility used initially in the program was modified so that flowing streams could be simulated. The configuration of the test facility, after the appropriate design changes were made, is shown in Figure 24.

The overall dimensions of the pool in which the water channel was built are 60 feet long, 15 feet wide and 15 feet deep. The test section is 45 feet long, 6 feet wide and water depth can be varied from 0 to 8 feet. Turning vanes were designed and installed to provide a uniform flow in the test section. Currents in the test leg of the facility can be varied from 0 to 4.5 feet per second in 1/10 of a foot per second increments.

The air manifold that represents a pneumatic barrier was constructed from a 3-inch diameter steel pipe with holes drilled along its length at 3-inch intervals to accept various nozzle configurations. Nozzles of the type shown in Figure 17 were used in this portion of the test program. Various nozzle sizes and spacings were considered during the test program. Moreover, the orientation of the jet with respect to the oncoming stream was also studied. A schematic of the manifold in the channel is shown in Figure 25. The air supply system was able to deliver from 0 to 600 scfm. Compared with previous test conditions in both CAL laboratory and river installations, this represented a tenfold increase in air supply capabilities. The system provides an air supply equal to the maximum recorded in the literature for pneumatic barrier tests as for example, Bulson (Ref. 1).

The pneumatic barrier system in the CAL water channel was evaluated in three stages. The first consisted of determining the stream velocity distribution at given cross sections in the channel. The second stage concerned the formation of a surface stagnation zone by the barrier-induced current for various water speeds. The third stage determined the conditions under which oils could be restrained.

MODELING

To ensure correct modeling of the fluid flow patterns in a pneumatic barrier system, the important physical parameters in the system must first be determined. An examination of the equations describing the fluid motions indicates that the variables of importance are $U, \zeta_w, \Delta\zeta, \dot{m}, g, L, A$

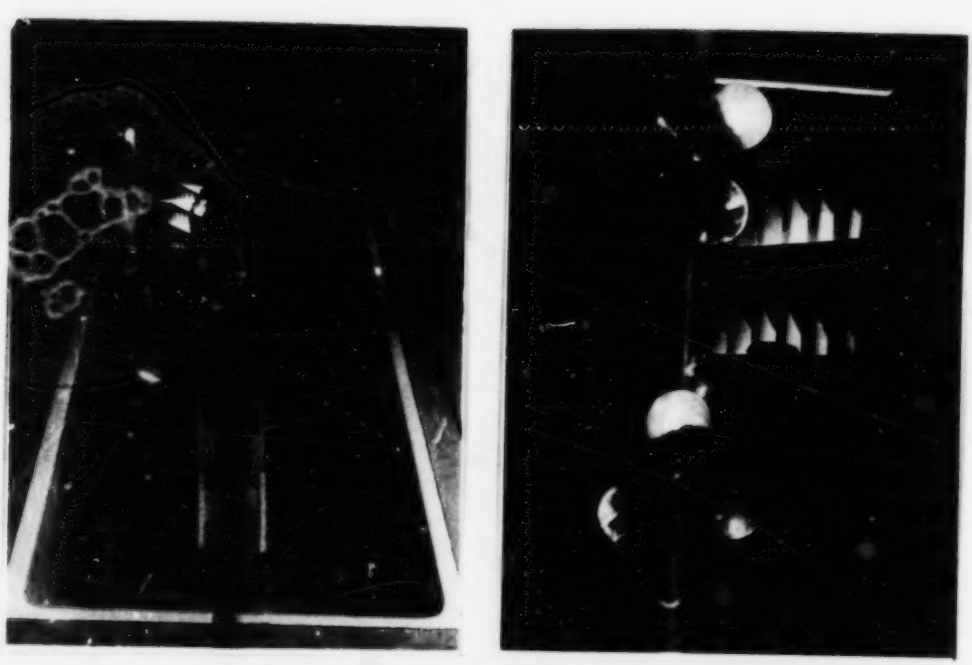


Figure 24 WATER CHANNEL TEST FACILITY

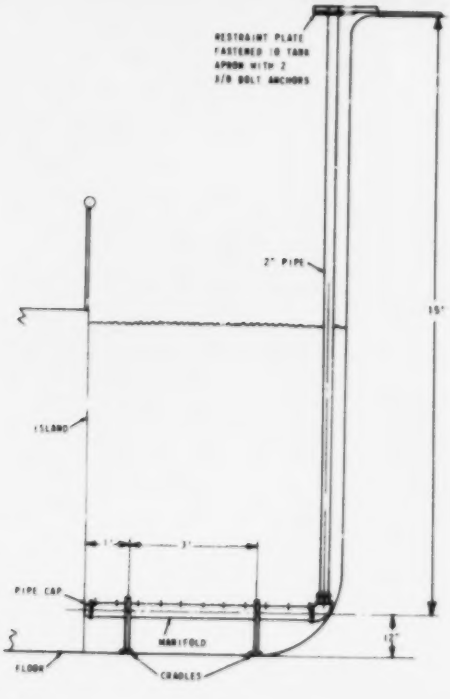


Figure 25 SCHEMATIC OF AIR MANIFOLD IN WATER CHANNEL

Where

U	=	stream velocity
ζ_w	=	density of water
$\Delta\zeta$	=	the density difference between water and air-water mixture
$\dot{m}$	=	mass flow rate of air
g	=	acceleration due to gravity
L	=	a characteristic length scale
A	=	cross sectional nozzle area

The quantity $\Delta\zeta$ rather than the density of each medium, namely water to air, is important since only the density difference enters the equations through the buoyancy force term. For a pneumatic barrier, a dimensionless parameter known as the Richardson number can be shown (Ref. 12) to be of prime importance. The Richardson number is the ratio of buoyancy force induced by the air-water mixture to the inertia forces derived from the freestream velocity expressed as

$$R_i = \frac{gL}{U^2} \cdot \frac{\Delta\rho}{\rho_w}$$

The second and last parameter of importance in the pneumatic barrier system is the ratio of jet inertia force to freestream inertia forces (Ref. 13). The importance of the jet inertia can be indirectly evaluated by considering the effect of variation in jet direction on properties at the water surface. From experimental evidence shown in Figure 30 and Table 3, it is clear that jet momentum is not a factor in these studies, and hence the modeling of R_i was considered sufficient to ensure a correct modeling of the flow field in a pneumatic barrier system.

Table 4 shows some typical values for the Richardson number for various situations. In these calculations the characteristic length, L, is taken equal to the depth of the Buffalo River, 30 feet, at the site of the in-river tests.

TEST PROGRAM

Velocity Profiles

In this portion of the program, two single-propeller current meters simultaneously monitored velocities. One, a small Stevens meter, was placed in a fixed position in the channel to monitor the velocity. The second, an Ott C-1 propeller current meter, obtained horizontal and vertical velocity profiles in the channel. Two meters were used to ensure the constancy of the flow conditions at a representative point while the velocity profile was being measured at various stations across the flow. Figure 26 illustrates the coordinate systems used in this investigation. Samples of the velocity profiles measured in the channel for different positions and stream velocities are shown in Figures 27 through 29.

Table 3

MANIFOLD CONFIGURATIONS

CONFIGURATION	NOZZLE		ORIENTATION
	DIAMETER (in.)	SPACING (ft)	
A	0.125	1	UP
B	0.125	1	DOWN
C	0.250	0.5	DOWN
D	0.250	0.5	UP
E	0.250	1	UP
F	0.250	1	HORIZONTAL-UPSTREAM
G	0.250	1	DOWN
H	0.080	0.5	UP
I	0.080	0.5	DOWN
J	0.125	0.25	UP

Table 4

TYPICAL VALUES FOR RICHARDSON NUMBERS*

AIR SUPPLY RATE (scfm/ft)	u = 1.0 fps	u = 1.5 fps
	Ri =	Ri =
5	4.8	2.1
10	9.6	4.3

*THE RELATIONSHIP BETWEEN IN-RIVER RICHARDSON NUMBERS AND THOSE FROM LABORATORY EXPERIMENTS IS DISCUSSED IN THE SECTION ENTITLED "RESULTS OF TESTS ON SURFACE OILS."

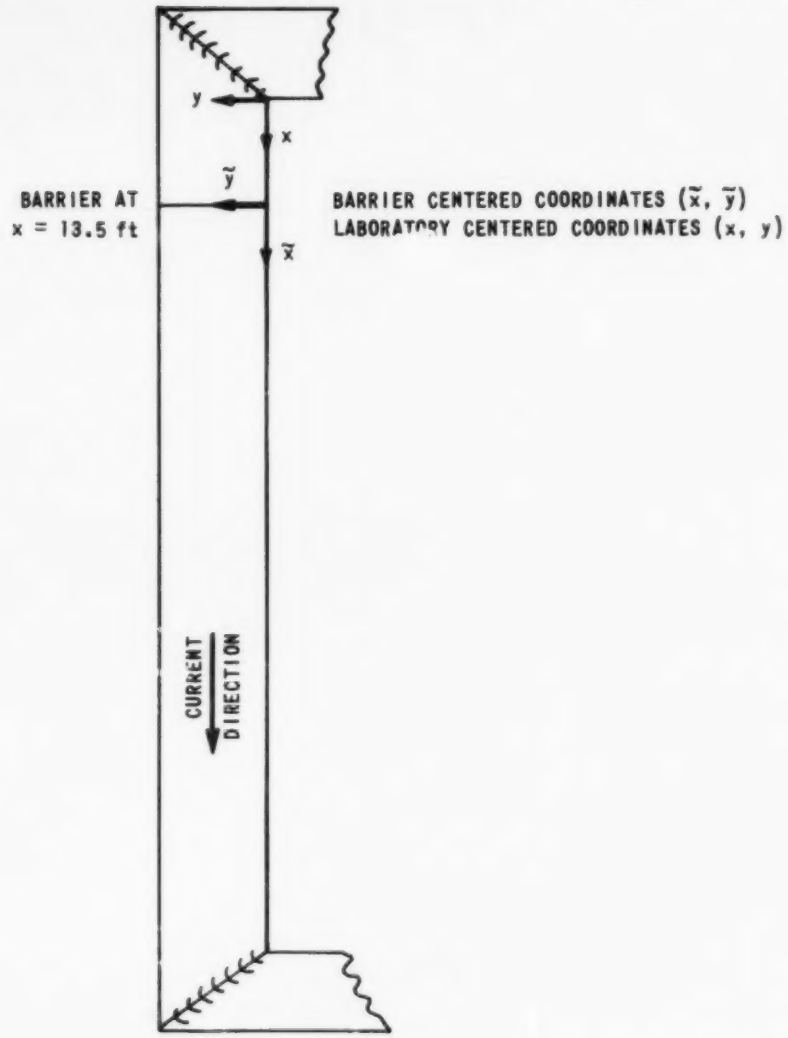


Figure 26 COORDINATES USED IN PNEUMATIC BARRIER INVESTIGATION

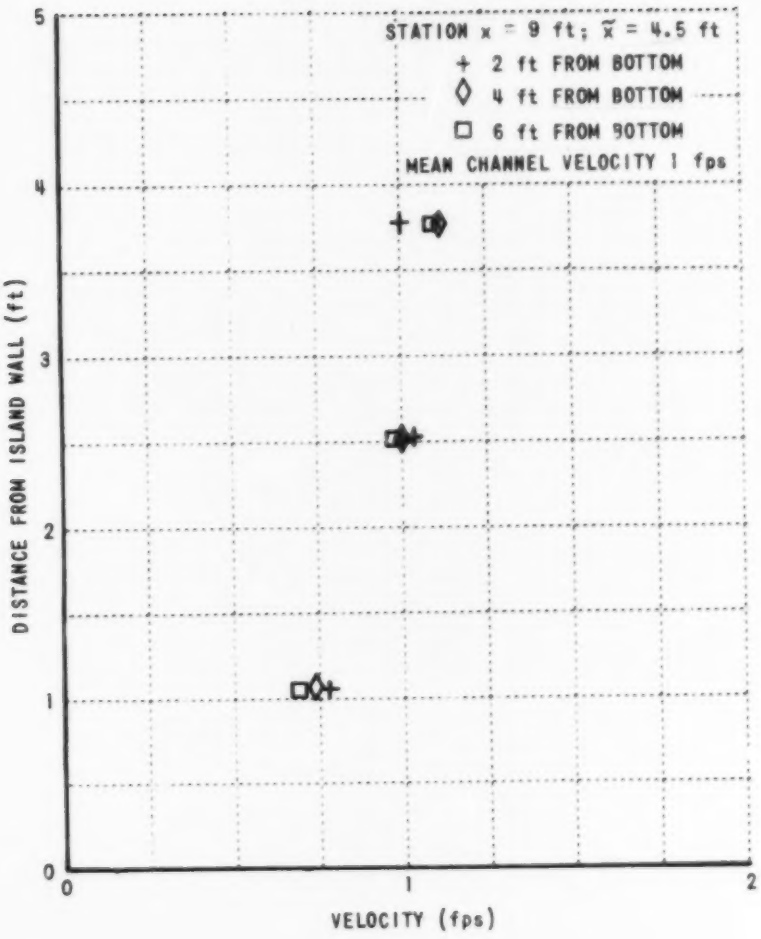


Figure 27 WATER CHANNEL VELOCITY PROFILE

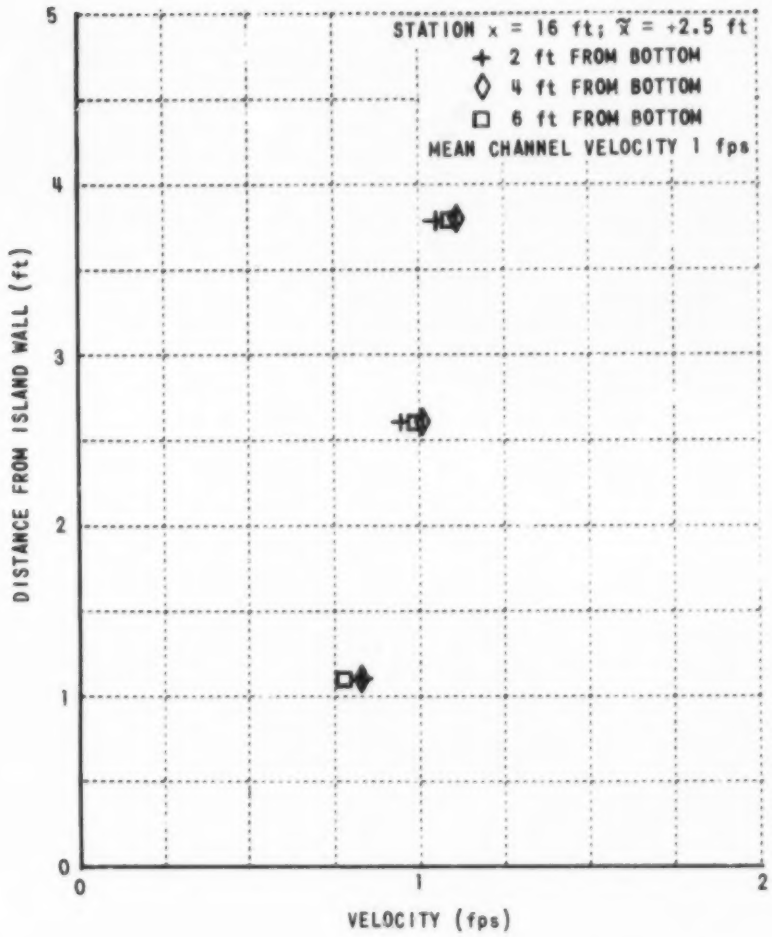


Figure 28 WATER CHANNEL VELOCITY PROFILE

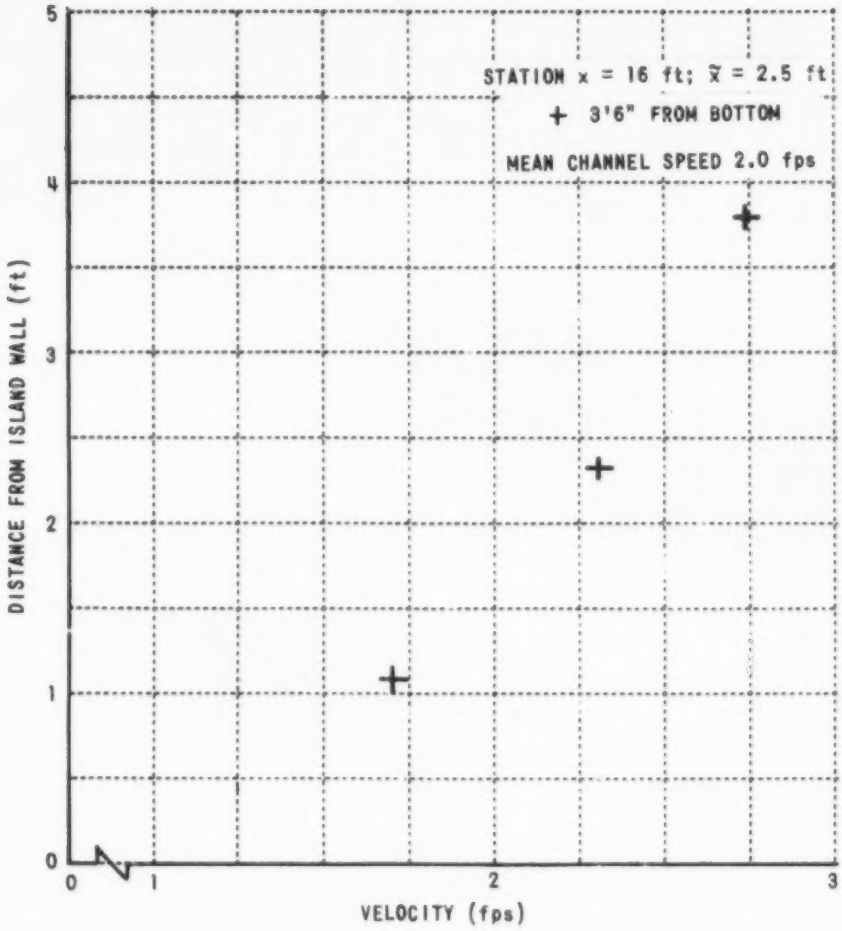


Figure 29 WATER CHANNEL VELOCITY PROFILE

Formation of Stagnation Zone

The second phase of this portion of the test program determined the conditions necessary to ensure the formation of a stagnation zone in the flow. The stagnation zone formed by the stream current and the current generated by the pneumatic barrier were examined for various combinations of stream current, orifice size, orifice spacing, and orifice orientation. The orientations examined were such that the orifices were pointing up, down, or horizontally upstream. The zone was visually observed by noting the position of styrofoam particles floating on the water.

Figure 30 is a plot of the distance, Δ, defined as the distance between the stagnation line and the upstream edge of the bubble pattern, versus air flow rate, expressed in terms of standard cubic feet of air per minute per foot of manifold. The parameters varied are the freestream current and the nozzle orientation. Table 3, which describes the various manifold configurations, and Figure 30 show that the quantity Δ is insensitive to the orientation of the air supply manifold. Since Δ is directly related to the surface velocities generated by the air-water mixture, one can infer that the induced surface velocities are also independent of nozzle orientation. The net effect of this observation is that for conditions investigated, buoyancy forces dominated the jet inertial forces. This indirectly implies that the depth of submergence is not an important consideration in the interpretation of the results. From the tests performed in the Buffalo River, as well as those conducted in the water channel, it is clear that the effect of supply pressure on the position of the stagnation line is small.

Testing of Oils in a Channel

After investigating the capability of a pneumatic barrier to form a stagnation line in a current, the ability of the system to restrain surface oils was examined. To control the area in which the oil was to be spread, as well as to facilitate underwater photography of the oil slicks, two Plexiglas plates were designed and built to fit into a portion of the test section. This configuration had a beneficial effect of limiting the testing of oils to a portion of the channel where a uniform velocity could be ensured. The plexiglass plates, 3/16 of an inch thick, 12 inches high, and 9 feet long, were placed vertically into the water and separated by a distance equal to 2.5 feet. The plates were immersed approximately 10 inches beneath the water surface. A photograph showing the placement of this channel in the test leg of the CAL facility is presented in Figure 31. To assess the effects of these plates on the flow of water in the test section, a dye was injected near the entrance of the channel at near- and sub-surface positions. The flow between the plates was virtually undisturbed by the presence of the Plexiglas walls as was verified by streamline dye patterns.

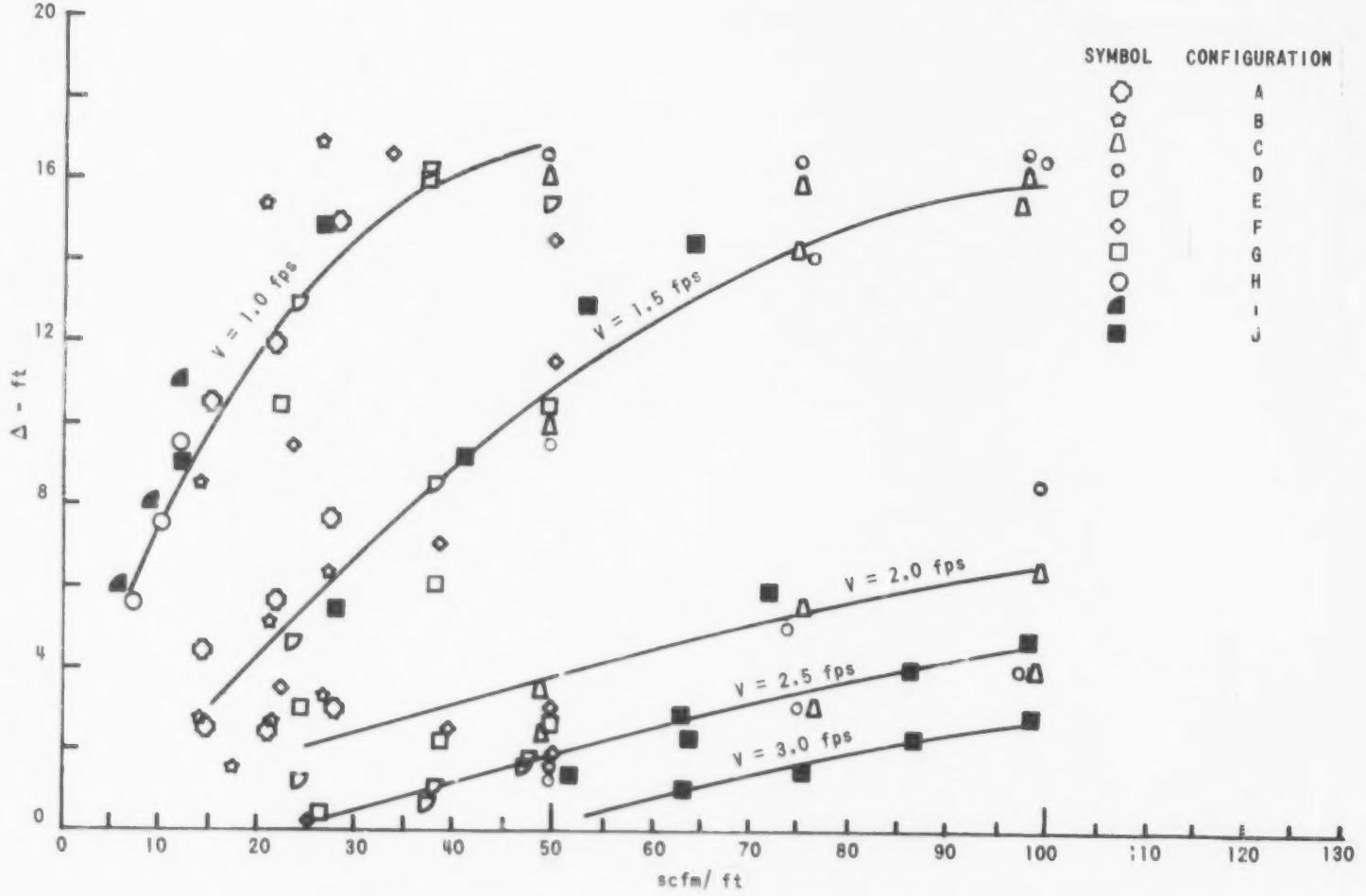


Figure 30 EFFECT OF VOLUMETRIC FLOW RATE ON Δ

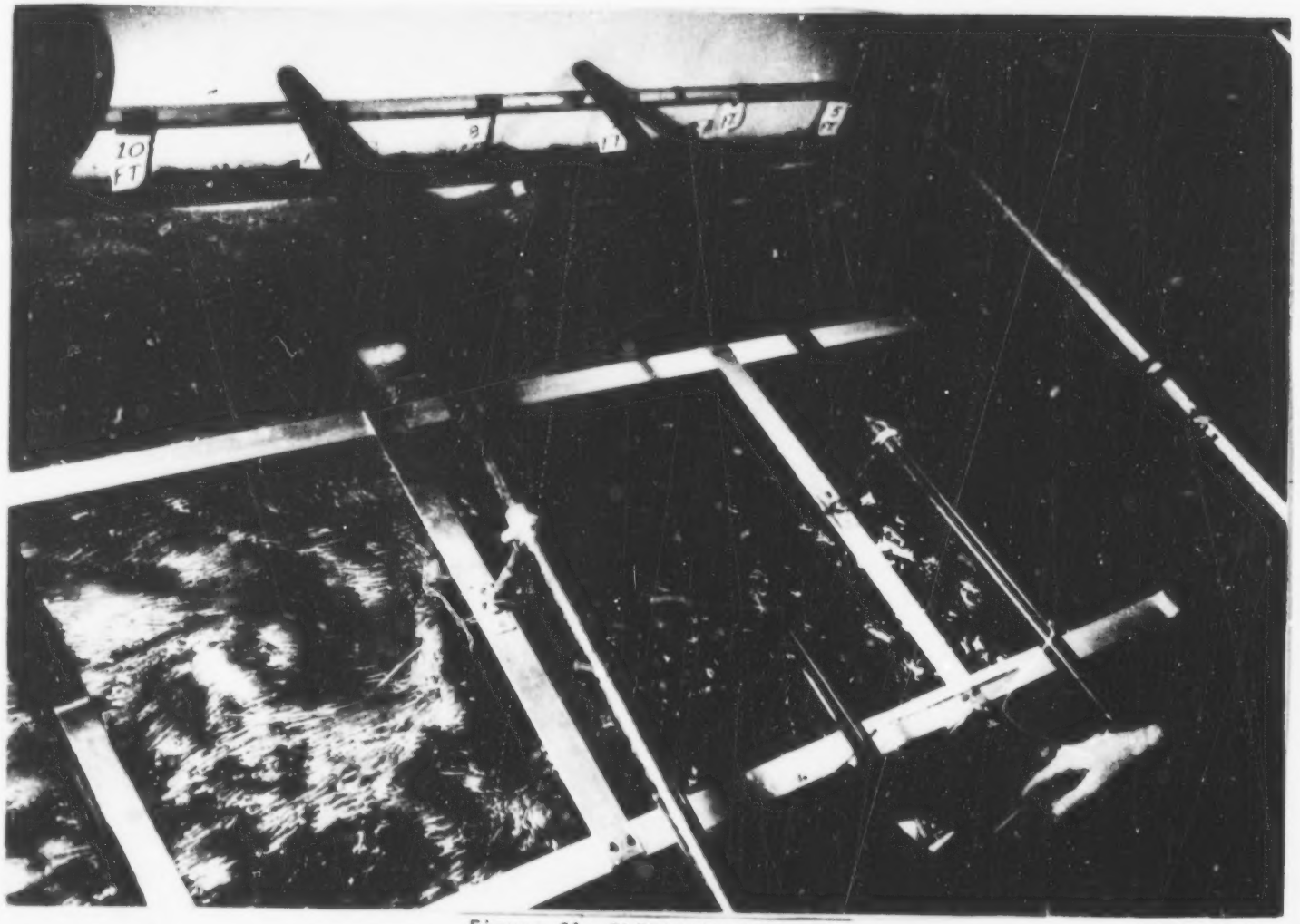


Figure 31 PLEXIGLAS CHANNEL

The test procedure for investigating the capability of a pneumatic barrier configuration to restrain oil consisted of the following steps:

1) Establish a steady current in the test section of between 0.3 and 0.5 ft/sec

2) Adjust the air supply to the manifold to form a stagnation line contained within the length of the Plexiglas channel

3) Carefully pour a quantity of oil to be tested on the water surface

4) Wait until the oil has surfaced and spread between the walls of the plexiglass channel

5) Photograph the sub-surface oil slicks

6) Photograph the above-surface oil pattern

7) Incrementally increase the current in the test facility and adjust the air supply to retain the stagnation zone within the length of the Plexiglas channel.

Following Step 7, Steps 5 and 6 were repeated. Step 7 was repeated for various increments in stream current until the slick was no longer restrained. At each stage in the test, air and water temperature, air pressure, mass flow rate, and water velocity were recorded. The oils that were tested were chosen to represent a range of viscosities and specific gravities. A listing of the oils tested, together with their physical properties, is shown in Table 5.

Table 5
PROPERTIES OF OILS TESTED

OIL TYPE	VISCOSITY (CENTISTOKES @ 100°F)	SPECIFIC GRAVITY (60/60°F)
#2 FUEL	29	0.865
#6 FUEL	970	1.0
BACHAQUERO CRUDE	324	0.95
SOUTH LOUISIANA CRUDE	4.5	0.84

Results of Tests on Surface Oils

Table 6 shows the results of the oil-restraining capabilities of the pneumatic barrier as determined from tests in the laboratory facility. In the process of determining the speed at which the barrier became ineffective, visual inspection of the surface downstream of the turbulent zone was made in conjunction with surface and sub-surface photographic techniques. The surface downstream of the turbulent zone was an effective indicator of the barrier's ability to restrain oil since oil particles which passed through the barrier resurfaced and thus an estimate of the amount of oil passing the barrier could be made. Figures 32 and 33 are examples of the type of surface and sub-surface photographs taken during this test program. These figures note the stream conditions and air flow conditions at the time the photographs were taken.

Table 6

FAILURE VELOCITIES FOR DIFFERENT OIL TYPES

OIL TYPE	CURRENT AT WHICH SERIOUS BREAKTHROUGH OCCURS
#2 FUEL	0.7 fps
#6 FUEL	1.3-1.5 fps
BACHAQUERO CRUDE	0.8 fps
SOUTH LOUISIANA CRUDE	1.0 fps

In the section on modeling, the Richardson number was discussed during comparison of water channel and river results. For accurate modeling, the Richardson number must be the same in both instances. The Richardson number was defined as

$$R_i = \left(\frac{gL}{U^2}\right) \cdot \frac{\rho}{\rho_w}$$

For similarity of the flows in the test channel (C) and in the river (R)

$$\frac{(R_i)_R}{(R_i)_C} = 1 = \frac{L_R}{U^2_R} \cdot \frac{(\Delta\rho)_R}{(\Delta\rho)_C} \cdot \frac{U_C^2}{L_C}$$

Thus

$$U_R^2 = U_C^2 \cdot \frac{(\Delta\rho)_R}{(\Delta\rho)_C} \cdot \frac{L_R}{L_C}$$

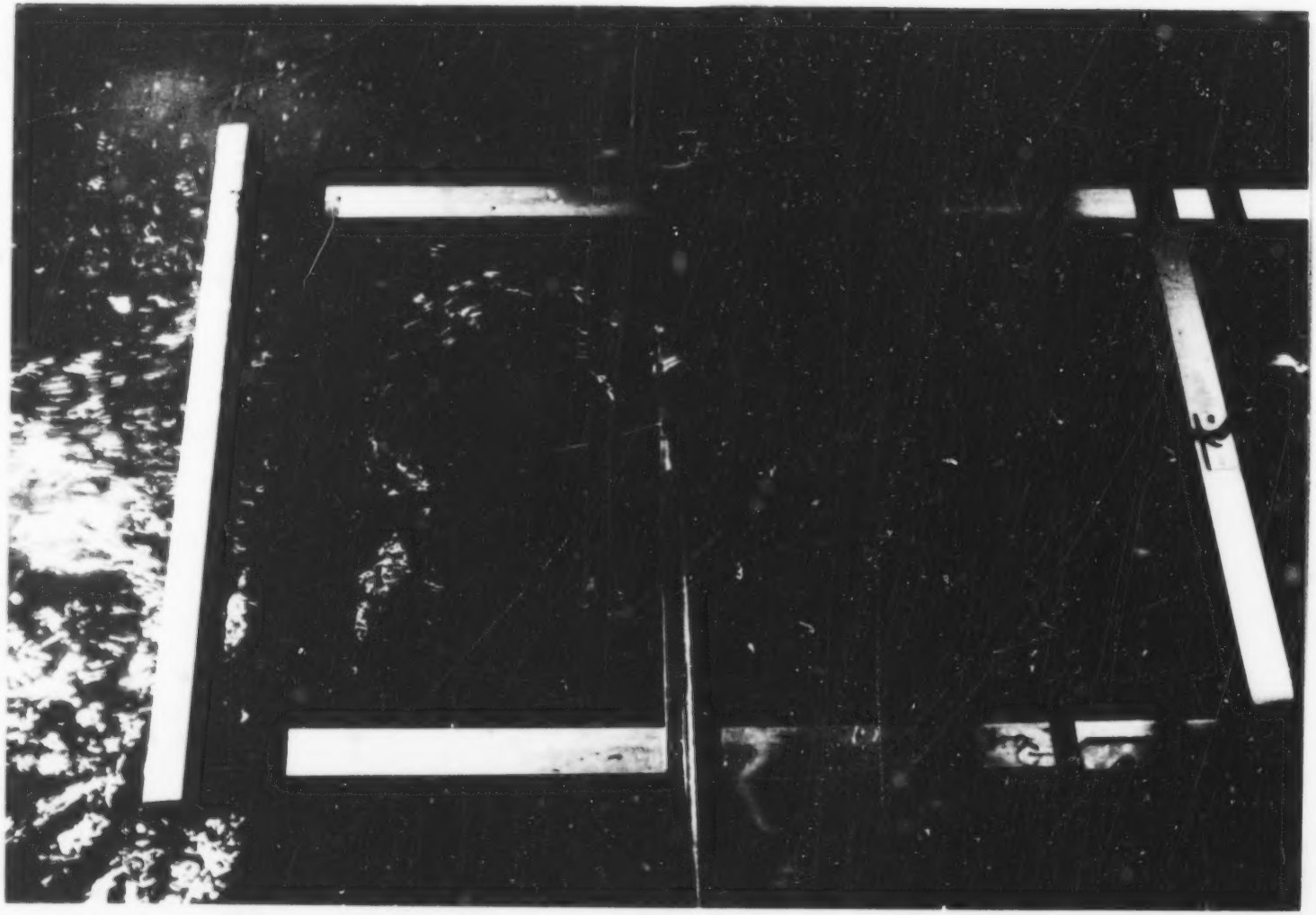


Figure 32 SURFACE PHOTO #2 FUEL V = 0.7 fps

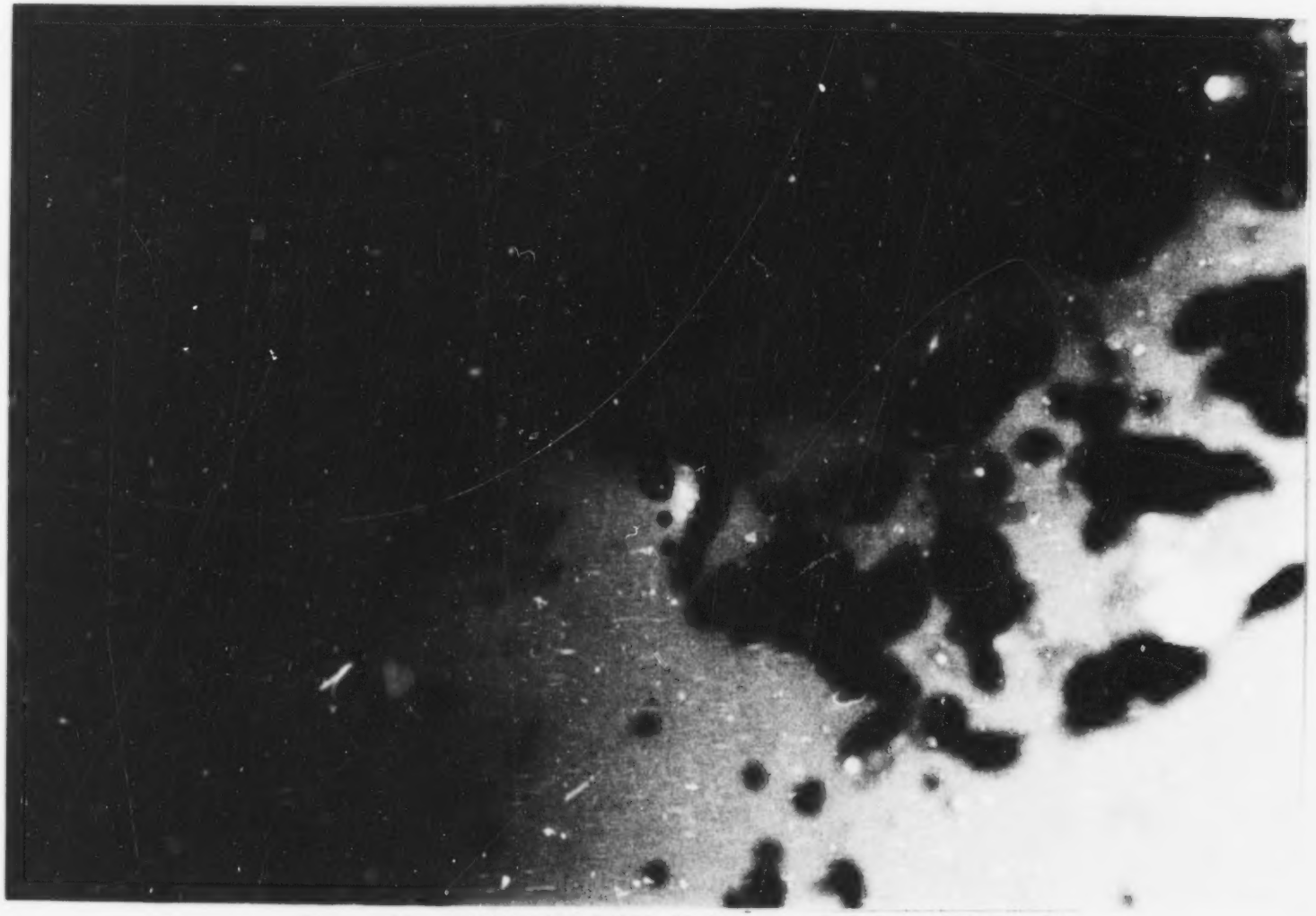


Figure 33 SUBSURFACE PHOTO #2 OIL V = 0.7 fps SCALE ≈ 2X

Assuming that the rising plume is confined by a constant angle, ϕ, triangular area, the density of the air-water mixture can be approximated by the following equation

$$\rho_{aw} = \rho_{aw} \left[1 - \frac{\dot{M}}{UL \tan \phi/2}\right]$$

where U is a value for the vertical velocity of the air-water mixture and $\dot{M}$ is the mass flow rate of air in standard cubic feet per second. Calculating $(\Delta\rho)_R/(\Delta\rho)_C$ and using the fact that the velocity of rise of the air-water mixture and the plume cone angle is the same in the river and channel, one can write

$$U_R^2 = U_C^2 \left(\frac{\dot{M}_R}{\dot{M}_C}\right)$$

For $U_C = 1$ fps, which was a typical velocity for barrier failure, $M_R = M_C$ from experimental results. Thus one could conclude that the velocity modeled in the channel for one foot per second flow corresponds to a velocity of one foot per second in the river for mass flow used.

PNEUMATIC BARRIER FAILURE MECHANISMS

During the investigations, three modes by which surface oil can pass a pneumatic barrier were identified. The first mode is due to an interaction between vortices shed from the turbulent zone and the restrained oil slick. The second mode is due to the characteristics of the flow field in the vicinity of the stagnation zone. The third mode is related to tearing and subsequent mixing of an oil slick.

The first mode of failure was observed once during the river phase of the test program when the river current was more than 1.4 fps. To understand the cause of this mode of failure, consider Figure 34, a photograph of the position on the river where the air bubbles surface. Consider the cellular pattern and in particular the concentrated bubble pattern that exists along the edges of the cells which extend upstream and downstream of the bubble zone. If an inspection of these edge concentrations is made in detail, it is found that they contain vortices whose strength and intensity decreases as they are convected away from the bubble pattern. For high stream currents the distance between the oil slick and the turbulent zone, represented by the quantity Δ decreases. For a sufficiently high value of river current the vortices shed from the turbulent zone are convected into the oil slick. At the position of intersection the surface oil may be pulled below the surface in the form of droplets. If the droplets are carried more than a few inches below the surface, they may be easily convected through the rising air current by the main stream current. Figure 35 is a superposition (Figure 35c) of the conjectured velocity profile generated solely by the air barrier (Figure 35a) and that of the river current (Figure 35b). D_1 represents the depths at which the horizontal velocity in a flow generated by a pneumatic barrier changes direction without a superimposed river current; D_2 represents the change with a current. The distance $D_2 < D_1$. As the current in the river increases, $D_2 \rightarrow 0$, and the distance beneath the surface to which the oil must be pulled before it can be convected through the varrier decreases as the current increases. Once the oil droplets are out of the zone of high shear; i.e., the vortex, they rise to the surface and proceed in the direction of current.

Additional observations of this mode of barrier failure were made in the course of the experiments run in the water channel. The nonuniform character of the current generated by the rising air water plumes causes the production of zones of vorticity that are convected by the barrier-induced currents upstream into the floating oil slick. For some cases, in particular the #2 fuel oil, the vortices intersecting the surface film pulled the oil droplets from one to two feet beneath the water surface. Photographs of such a failure mechanism are shown in Figure 36 .

Figure 34 TYPICAL SURFACE BUBBLE PATTERN

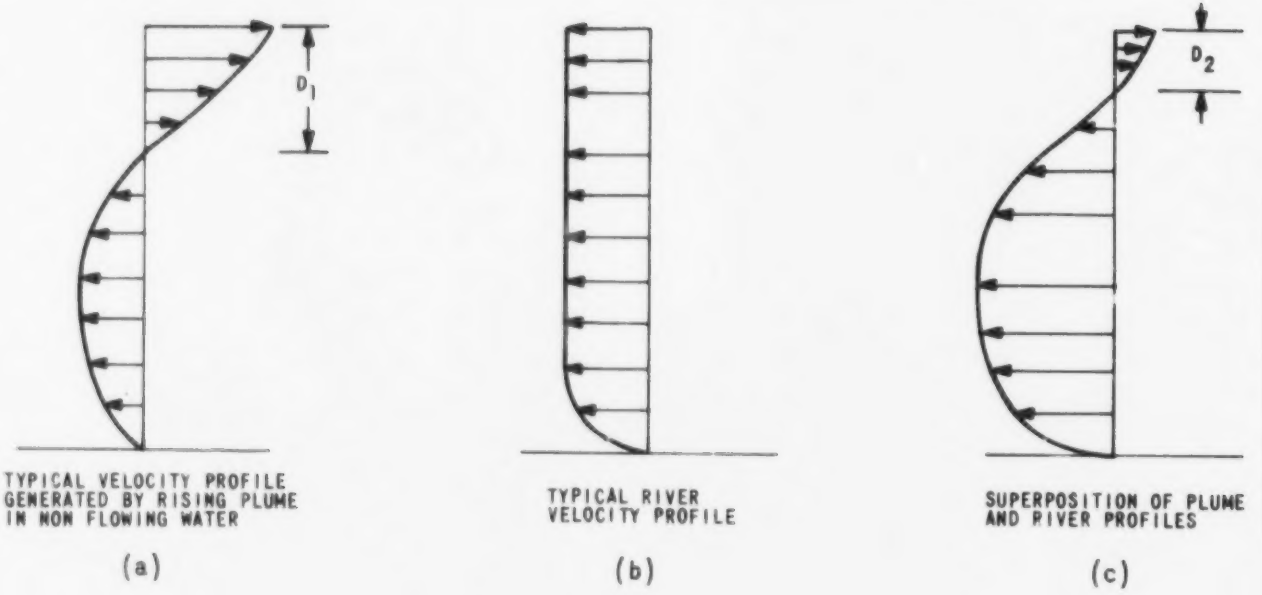


Figure 35 APPROXIMATION OF THE VELOCITY PROFILE GENERATED BY PNEUMATIC BARRIER OPERATING IN A RIVER CURRENT

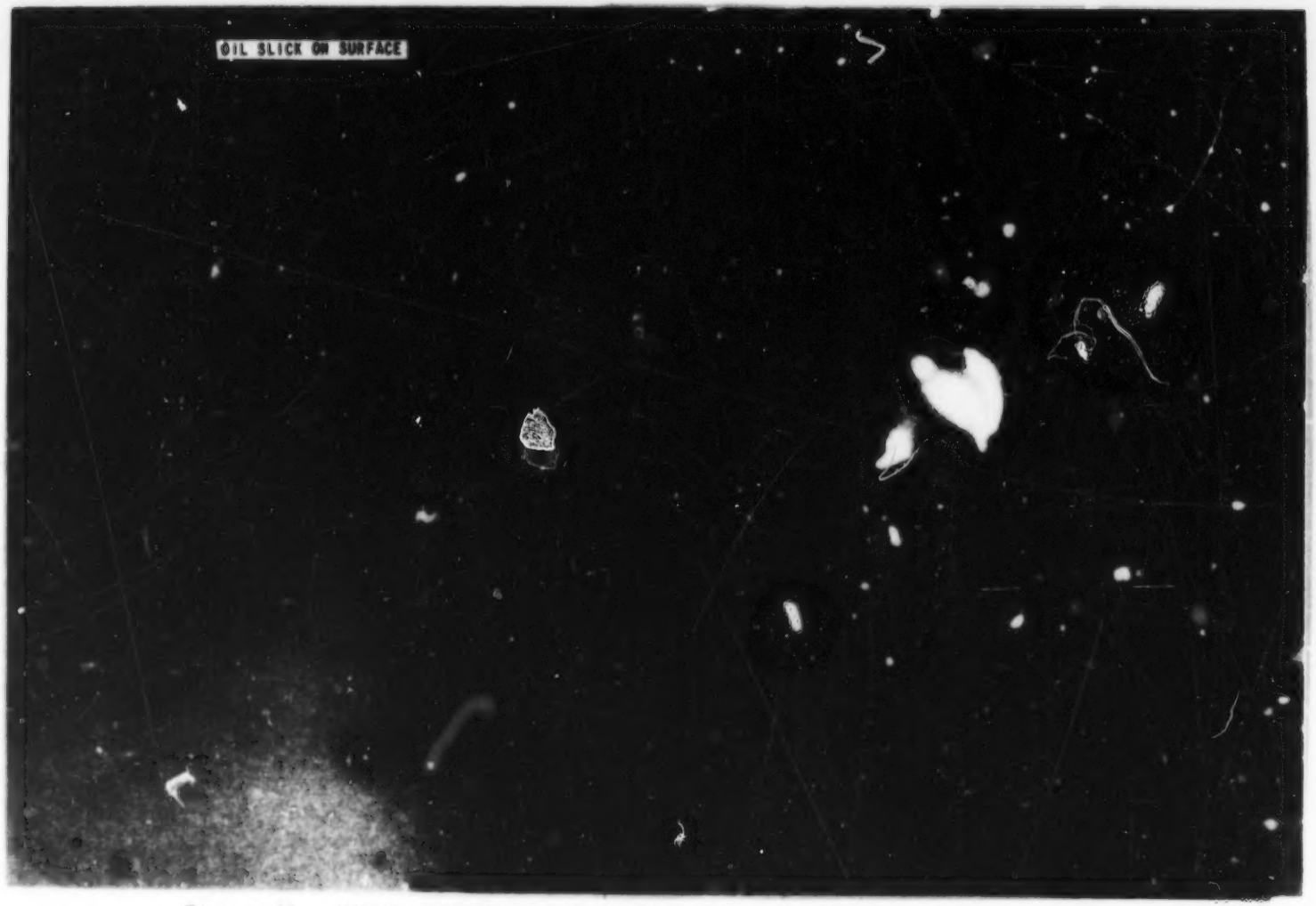


Figure 36 VORTEX EFFECT ON OIL SURFACE (VIEWED FROM JUST BELOW SURFACE)

The second mode of barrier failure is due to the characteristics of the flow pattern in the neighborhood of the stagnation zone. A schematic of the flow pattern in the zone is shown in Figure 37. As the main stream is deflected downward by the current generated by the barrier, the flow in the area noted by A undergoes a vertical acceleration. As the oil film becomes thicker, the bottom particles of oil are subjected to a downward accelerating force as well as a horizontal shear caused by the water moving past the stagnating oil. For sufficiently high currents and oil film thicknesses, the forces due to shear and the downward acceleration of the flow may equal the buoyancy and viscous forces tending to retain the oil slick on the surface. This mode of failure can be especially important in the restraint of thick oil films. The actual determination of the degree of this effect in any situation is difficult to assess. From visual observations of the mode of failure in the water channel tests, one would say that the vortex interaction mode was dominant.

The third mode of failure consists of surface shed tearing followed by mixing of the resulting small patches of oil with water. The mixing is effected by currents induced by the pneumatic barrier. A sequence of photographs taken in the course of the river experiments, Figures 38, 39 and 40, illustrates how this mode of failure works. First a streak of oil moves down the river until it is diverted by the barrier-induced current. This causes the slick to spread across the stream. The leading edge of the slick is subsequently torn into small patches by the currents generated by the barrier near the stagnation zone. These patches are continually made smaller by the action of the current and ultimately mixed with the bulk of the water. This action may take place very far from the barrier; for example, sixty feet, and is not related to the vortex interaction mode noted above. As a typical example this mechanism of failure takes place over many minutes in contrast to the very rapid failure modes described previously.

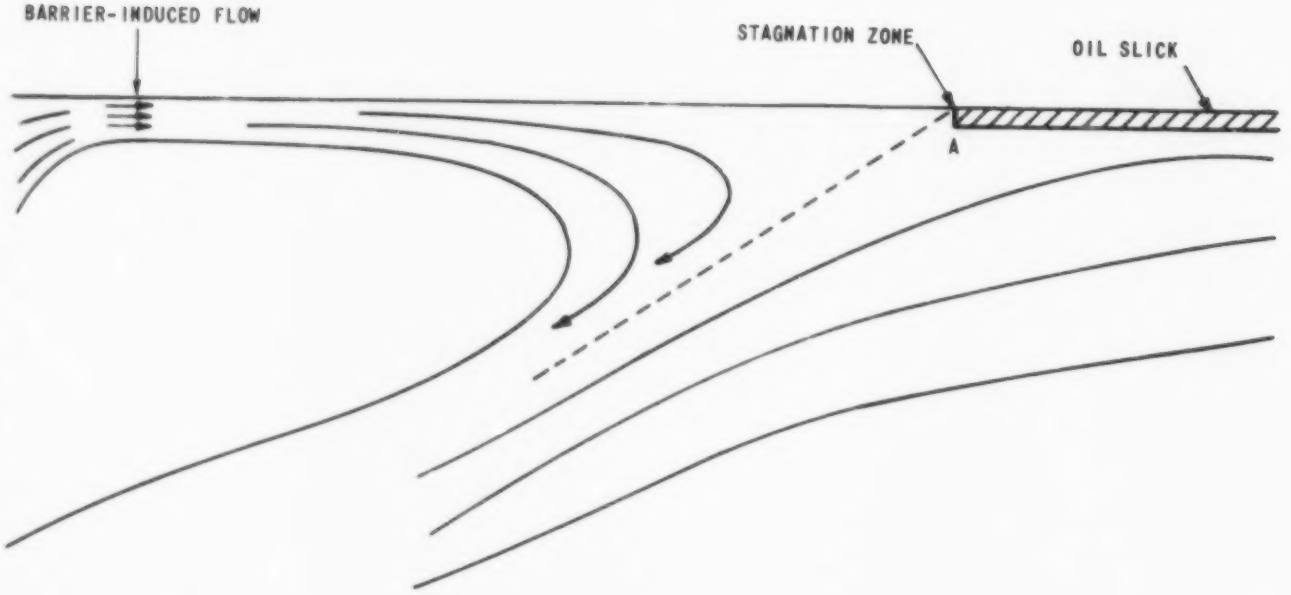


Figure 37 NEIGHBORHOOD OF THE STAGNATION ZONE

Figure 38 Ist STAGE FILM TEARING

Figure 39 2nd STAGE FILM TEARING

Figure 40 3rd STAGE FILM TEARING

POWER REQUIREMENTS

From the laboratory investigations conducted in the CAL water channel, as well as from the full-scale measurements in the Buffalo River, it is possible to specify the power requirements for an operational pneumatic barrier system. But to do this, it is first necessary to know the horsepower required to compress a given quantity of air to a given pressure. This information is shown in Figure 41, wherein the horsepower is shown as a function of the volumetric flow rate for parametric variation of supply pressure. If one assumes that the stagnation line must be at least 4 feet from the leading edge of the bubble pattern, then from Figure 30, the air flow rate required for a given stream current can be established. Combining the air flow rate with the data in Figure 41, the power required for various supply pressures can be estimated. A combination of the data from Figures 30 and 41, for assumed values of Δ equal to 4 feet and supply pressure of 20 psig, is shown in Figure 42. For a typical river like the Buffalo River, which is 200 feet wide, the air flow to form a stagnation zone in a 2-foot per second current would be 52.5 scfm per foot or 10,500 scfm for the river. Power required to supply this quantity of air at 20 pounds per square inch is 630 horsepower. For many cases, this quantity of air would not be economically feasible. In addition, it should be noted that the power required, as derived from Figure 42, is related to the formation of a stagnation zone in the river. This is a necessary, but insufficient, condition to ensure the stoppage of oils.

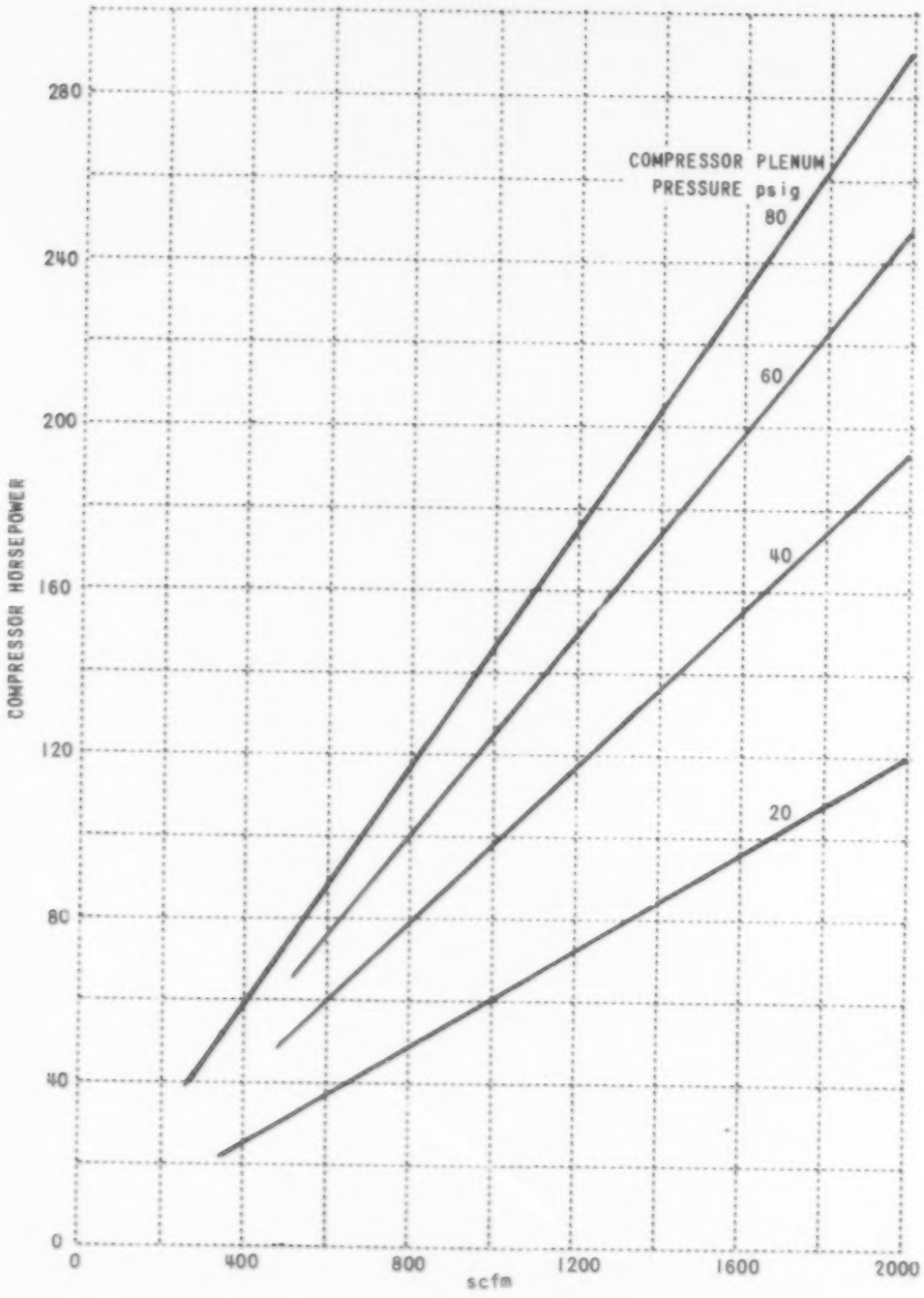


Figure 41 HORSEPOWER vs VOLUMETRIC FLOW RATE

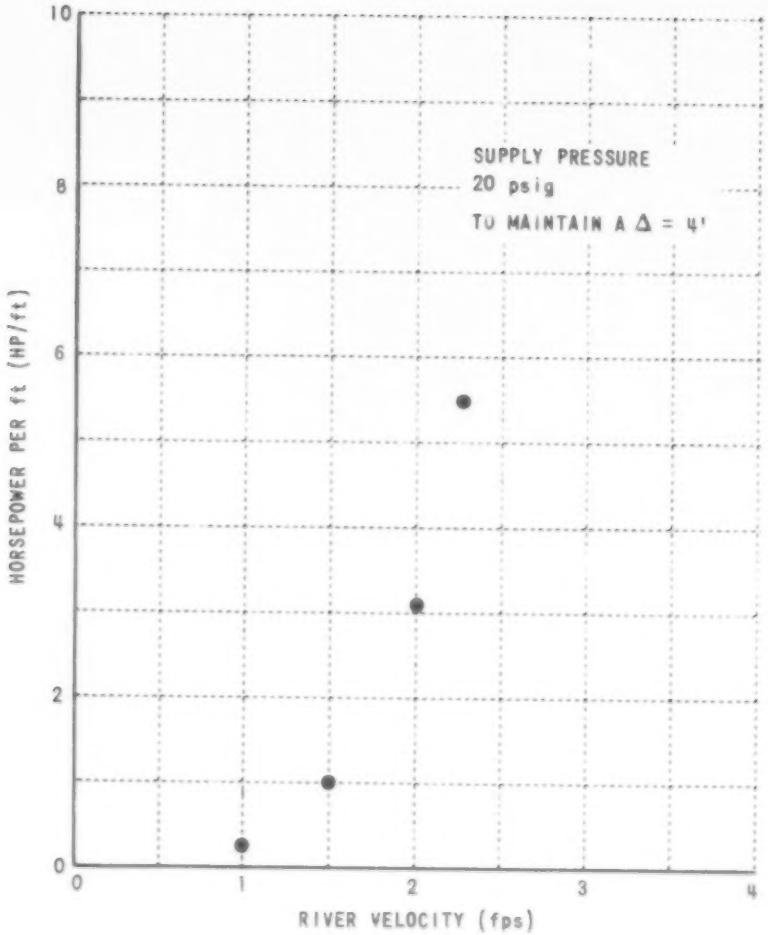


Figure 42 HORSEPOWER vs RIVER CURRENT

ACKNOWLEDGEMENTS

This project was carried out by Cornell Aeronautical Laboratory, Inc. with financial support of the Environmental Protection Agency.

The author wishes to acknowledge the significant contributions made by A. Sowyrda (formerly of CAL) to the design of the in-river pneumatic barrier system. Also, the author wishes to thank the Water Quality Office of the Environmental Protection Agency for support and H. Bernard and R. Keppler of the W.Q.O. for their encouragement; Mr. John F. Downing, Commissioner of Public Works, City of Buffalo, for his continued interest and cooperation in making available the personnel required to assist in the construction and installation of the barrier; Mr. Thomas J. Lyons of the Engineering Division, Public Works Department, for his help in designing the barrier as well as in planning and supervising its installation; and finally, Dr. Robert C. Ziegler, CAL Project Manager, Mr. R. L. Frank (formerly of CAL), Assistant Project Manager, for their overall assistance, recommendations and advice throughout the course of this phase of the program.

Preceding page blank

REFERENCES

1. P. S. Bulson, "Currents Produced by an Air Curtain in Deep Water," The Dock and Harbor Authority, May 1961.

2. James L. Green, "Pneumatic Breakwaters to Protect Dredges," Journal of the Waterways and Harbor Division, Proceedings of the American Society of Civil Engineers, May 1961.

3. Walter Hensen, "Model Tests with Pneumatic Breakwaters," The Dock and Harbor Authority, June 1955.

4. A. H. Laurie, "The German Experiments on Pneumatic Breakwaters," The Dock and Harbor Authority, June 1955.

5. J. T. Evans, "Pneumatic and Similar Breakwaters," The Dock and Harbor Authority, December 1955.

6. J. T. Evans, "Pneumatic and Similar Breakwaters," Proceedings of the Royal Society of London, A231, 1955.

7. G. I. Taylor, "The Action of a Surface Current Used as a Breakwater," Proceedings of the Royal Society of London, A231, 1955.

8. Michinori Kurihara, "Pneumatic Breakwater II," Proceedings of Second Conference on Coastal Engineering in Japan, November 1955.

9. Michinori Kurihara, "Pneumatic Breakwater III," Proceedings of Second Conference on Coastal Engineering in Japan, 1955, Trans. Univ. of Calif. Dept. of Engineering, Institute of Engineering Research, Wave Research Laboratory Technical Report Series 104, Issue 5.

10. J. B. Schijf, "Pneumatic Breakwaters to Protect Dredges," Journal of Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, November 1961.

11. Henry B. Simmons, "Potential Benefits of Pneumatic Barriers in Estuaries," Journal of the Hydraulics Division, Proceedings of American Society of Civil Engineers, May 1967.

12. G. K. Batchelor, "The Conditions for Dynamical Similarity of Motions of a Frictionless Perfect-Gas Atmosphere," Quarterly J. Royal Meteorological Society, LXXIX, 1953.

13. Loh-Nien Fan, "Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids," CIT Dev. of Eng. & Applied Sci., Rept. No. KH-R-15, June 1967.

Preceding page blank

14. R.E. Baier, E.A. Gasiecki, R.P. Leonard, and E.J. Mack, "Sampling and Identification of Pollutant Oils in Industrial Watercourses," Cornell Aeronautical Laboratory, Inc., for the City of Buffalo and the Water Quality Office of the Environmental Protection Agency (Program No. 11020 DJG, Grant No. WPRD 263-01-68).